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A study of the relationship between engineering design and measurement technology

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A study of the relationship between engineering design and measurement technology

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This thesis is dedicated to my parents, my wife, and my son.

Abstract

Engineering design and dimensional measurement tend to occur at opposite ends of the product creation process. As a result, the dialogue may sometimes be poor, and can lead to the production of features that are difficult to measure, adding unnecessary cost and risk to the business. In response, the EngD research aims to identify ways in which the relationship between these activities can be strengthened. An emphasis was placed on product lifecycle management (PLM), due to the sponsor's desire to maximise the value of their existing investments in this area. Since the problem is complex, and seemingly intractable, a mixed methods approach was adopted in which laboratory experiments were interwoven with small-scale interventions within industry.

The research began with the development of a theoretical framework, labelled 'PLM-integrated dimensional measurement' (PiDM). The framework builds on existing literature, whilst incorporating issues identified by stakeholders. Test cases were structured and executed against the framework in order to identify technology gaps; key amongst which was the need to improve measurement planning for coordinate measuring machines by incorporating uncertainty evaluation techniques. Four interconnected investigations were then carried out in an industrial setting to explore measurement capability in practice. The findings from these investigations informed subsequent development of an uncertainty-based measurement planning system. The system brings together commercially available simulation software and measurement programming software into a PLM environment. It allows features to be categorised according to their 'measurability', providing quantitative data for verification planning and engineering design.

The EngD concludes with an industrial case study, investigating potential routes to deployment. This case study provided the data needed to commission a further two year programme of research into the topic, formally engaging the sponsor organisation's strategic metrology and PLM solution providers. This new research programme is structured around the PiDM framework.

Author’s declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate’s own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

Signed Date

Acknowledgements

The research presented in this thesis would not have been possible without the support of many people. I cannot list everyone, and if a name is not mentioned this should not be taken as a lack of gratitude, rather a lack of space.

I would like to begin by acknowledging my supervisors, who have reviewed and debated numerous iterations of the research. Prof. Paul Maropoulos, my lead academic supervisor, has given constant encouragement and guidance throughout the EngD; permitting me the freedom to explore ideas, yet reining me back in as was sometimes necessary. Prof. Andrew Graves, my second supervisor, provided thought-provoking advice on the systems aspects. I have also had the great benefit of two industrial supervisors: Nick Orchard and Neil Tatman. Nick's metrology expertise coupled with Neil's knowledge in product lifecycle management has been invaluable. Nick recently retired from his role as the measurement process owner at Rolls-Royce plc, yet continued to participate in reviews and offered advice, for which I am sincerely grateful. Neil then volunteered to take on the supervisor role, and embraced the commitment with integrity and enthusiasm.

I have had the privilege to work with a large number of people at Rolls-Royce plc. Dr. Jose Garcia and Chris Bell introduced me to an important design integration project during the early stages of the EngD. As measurement team leader for much of my EngD, Dr. Philip Bamforth and his colleagues have offered considerable support. Fellow EngD students and alumni, including Rocky Verma, Dr. Hugo Lobato, and Dr. Paul Gibbons have been very supportive, and there are elements of Hugo's research that I have followed up in my studies. I would also like to thank the many dedicated professionals in the Rolls-Royce 'Measurement Excellence' community of practice; individuals like George Brown, who have been happy to spare their time to discuss issues pertinent to the research.

I am grateful to the co-authors on the papers produced during the research. This includes Prof. Juani Swart from the management school at Bath, Dr. Seb Giudice who heads up measurement systems analysis within Rolls-Royce plc, Dr. Alan Wilson from the National Physical Laboratory (NPL), and Dr. Bin Cai from the Manufacturing Technology Centre (MTC). Alan has gone far beyond the call of duty in programming and operating the CMMs at NPL, as referenced at the end of Chapter 5, in his own time. I truly appreciate the warm welcome and good advice I have had whenever visiting NPL, both from Alan and his colleagues. Bin has been similarly dedicated in his tenacity when arranging for CMM measurement work at the MTC in Chapter 4 and Chapter 6 to be conducted, and has been a source of inspiration through the many discussions we have had around the research topic.

The industrial setting of the EngD has led me into contact with experts within numerous commercial organisations. In particular, I must pay special thanks to the leadership team at Metrosage: Dr. Jon Baldwin, Prof. Kim Summerhays, and Daniel Campbell. Daniel has been on the receiving end of many phone calls and emails in helping me to understand the nuances of uncertainty evaluating software. Roland Dixon of Siemens has also offered helpful advice on the practical workings of product lifecycle management. I have also been privileged to have been welcomed by members of the Dimensional Metrology Standard Consortium, which has helped me to understand the wider application of the research.

I wish to acknowledge all those people who have quietly but efficiently facilitated the university administration. I am also grateful to those at the National Composites Centre, where I am currently employed, who have allowed me the flexibility to write up. Importantly, the research would not have been carried out without funding from the Engineering and Physical Sciences Research Council and Rolls-Royce plc.

Finally, and by no means least, I wish to offer my heartfelt thanks to my family and friends, for their unwavering support and patience. They helped me to see the big picture; apparently, 'the telephone is black'.

I am indebted to you all!

Publications and statement of contribution

The publications listed in this section have been written by the author. They are based on the research, and some of the content has been reused when preparing this thesis.

- Saunders, P., Giudice, S., Swart, J. (2014)

  “Identifying measurement knowledge and its relationship to engineering design”, *International Journal of Metrology and Quality Engineering*, Vol. 5 No. 2 (203). doi:10.1051/ijmqe/2014006.

  This paper reported on a case study which is referenced in Section 1.4.1. Dr. Seb Giudice wrote a portion of the discussion section, and Prof. Juani Swart advised throughout the review process.

- Saunders, P., Orchard, N., Maropoulos, P., Graves, A. (2010)

  “Integrated design and dimensional measurement: A review of the state of the art”, *Advances in Manufacturing Technology XXIV*, Durham, pp. 69-75.

  This review paper includes topics covered in Chapter 2. Nick Orchard, Prof. Paul Maropoulos, and Prof. Andrew Graves reviewed the paper.

- Saunders, P., Orchard, N., Maropoulos, P., Graves, A. (2012)

  “A user perspective on the Quality Information Framework”, *Advances in Manufacturing Technology XXVI*, Birmingham, Vol. 1, pp. 152-157.

  The interviews conducted for this paper are reported in Chapter 4, whilst the model that was developed in the discussion section of the paper is described in the opening sections of Chapter 6. Nick Orchard, Prof. Paul Maropoulos, and Prof. Andrew Graves reviewed the paper.

- Saunders, P., Cai, B., Orchard, N., Maropoulos, P. (2013)

  “Towards a definition of PLM-integrated Dimensional Measurement,” *Procedia CIRP*, Vol. 7, pp. 670–675. doi:10.1016/j.procir.2013.06.051.

  The derivation of the framework reported in this paper is used in Chapter 4. Dr. Bin Cai jointly facilitated a workshop where feedback was gathered; he also arranged for some of the experimental work to be carried out at the Manufacturing Technology Centre. Dr Bin Cai, Nick Orchard, and Prof. Paul Maropoulos reviewed the paper.

- Saunders, P., Verma, M., Orchard, N., Maropoulos, P. (2013)

  “The application of CMM based uncertainty evaluation software to machine tool inspection”, *Laser Metrology and Machine Performance X*, pp. 223-232.

  This paper was co-authored with an EngD colleague, Rocky Verma, since it was in an area which crossed the authors’ respective research topics. The content pertaining to the research in this EngD and written up by this author, Per Saunders, is presented in the study in Section 5.4. Nick Orchard and Prof. Paul Maropoulos reviewed the paper.

- Saunders, P., Wilson, A., Orchard, N., Tatman, N., Maropoulos, P. (2014)

  "An exploration into measurement consistency on Coordinate Measuring Machines", *Procedia CIRP,* Vol. 25, pp. 19-26. doi:10.1016/j.procir.2014.10.005.

  The majority of the material in this paper is included within Section 5.5. However, there are elements of the literature review from this paper which have been incorporated into Chapter 2. Dr. Alan Wilson carried out all of the experimental work in this section; however the experimental design and data analysis were completed by the author. Dr. Alan Wilson, Nick Orchard Neil Tatman, and Prof. Paul Maropoulos reviewed the paper, in addition to a technical and business review from the National Physical Laboratory.

Part of the research reported in Chapter 6 and Chapter 7 has previously been disseminated to project partners at the Manufacturing Technology Centre (for Chapter 6), and within internal reports at Rolls-Royce plc (for Chapter 7). The physical experiments in Chapter 6 were conducted by staff at the Manufacturing Technology Centre through Dr. Bin Cai; all the simulations and analysis were carried out by the author. In Chapter 7, the author was assisted by his industrial supervisor, Neil Tatman, when setting up workshops and hosting events. The documentation and analysis is entirely the work of the author.

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List of abbreviations

ASME	American Society of Mechanical Engineers
CAD	Computer-aided design
CMM	Coordinate measuring machine
CTC	Complex test case
DCM	Dimensional characteristics matrix
DFMEA	Design failure mode and effects analysis
DMIS	Dimensional measuring interface standard
EngD	Engineering doctorate
eTOM	Enhanced telecom operations map
FAI	First article inspection
FMECA	Failure mode effects and criticality analysis
FVRA	Feature verification risk assessment
GD&T	Geometric dimensioning and tolerancing
GPS	Geometrical product specifications
GRR	Gauge repeatability and reproducibility
GUM	Guide to the expression of uncertainty in measurement
ISO	International Organisation for Standardisation
NIST	National Institute of Standards and Technology
PDF	Probability density function
PiDM	PLM-integrated dimensional measurement
PFMEA	Process failure mode and effects analysis
PLM	Product lifecycle management
PMI	Product and manufacturing information
PUMA	Procedure for uncertainty management
QIF	Quality information framework
QM	Quality management
RPN	Risk priority number
SPC	Statistical process control
UES	Uncertainty evaluating software
UML	Unified modelling language
VIM	Vocabulary of basic and general terms in metrology
XML	Extensible markup language

Chapter 1 Introduction

1.1 Motivation

The business of creating high value engineering products is increasingly performed in a digital world. Products can be designed with 3D modelling tools. Their properties can be tested through simulation. Manufacturing plans and processes can be developed around the digital models. The vision of modern design and manufacturing is to minimise physical trials by optimising the use of digital technology (Stark et al., 2010).

The concept of managing a product as a digital object, from an initial idea to its disposal or reuse, is known as product lifecycle management (PLM). PLM can represent a substantial investment for companies. Yet whilst engineering design is frequently found to be immersed by PLM, dimensional metrology may often be found to languish outside (Maropoulos and Ceglarek, 2010).

Dimensional metrology, the science of measuring shape and size, is an inseparable part of manufacturing. Indeed, it could be regarded as the interface between the digital and the physical world. Whilst dimensional metrology is kept isolated from PLM, it remains remote from the design and manufacturing processes it supports. This can cause problems. For example, components may be released from design to manufacturing that contain features which are costly, or even impossible, to measure in order to verify against a specification; such features will be termed 'unmeasurables' in this thesis.

The presence of unmeasurables can have a number of consequences. For example:

- Non-critical features may be subjected to unnecessarily stringent measurement processes;
- There may be excessive iterations in design and manufacturing when components are redesigned in order to facilitate measurement;
- Concessions, rework, or scrap may result when components cannot be made to conform to specification;
- The risk of accepting non-conforming components may increase, with consequent risk of products underperforming, or system failure.

This research aims to identify ways in which engineering design and dimensional metrology can be brought closer together in order to reduce the presence of unmeasurables. Due to the stakeholders' desire to maximise the value of existing PLM investments, the focus of the research is on bringing the disciplines together through PLM.

1.2 Research environment

The research has been carried out within the manufacturing measurement team at Rolls-Royce plc, a well-known provider of gas turbine engines in the aerospace industry. The broader picture is that Rolls-Royce plc provides and manages power systems for its customers – this covers use in land, sea, and air for both civil and military applications. Taking the example of a Trent 1000 gas turbine engine, developed for the Boeing 787 Dreamliner aeroplane (Figure 1-1), it is clear that a great variety of physical components are involved, with complex interrelationships. An engine such as this will contain approximately 18,000 distinct components (Rolls-Royce, 2011a, p. 8); many of which have features that are critical to performance, safety, and life. Rolls-Royce plc has retained manufacture of the more 'difficult' components in house (Langston, 2006), and is reliant on a robust system of verification and validation to ensure that these manufactured components meet the intended design (National Measurement Office, 2010).

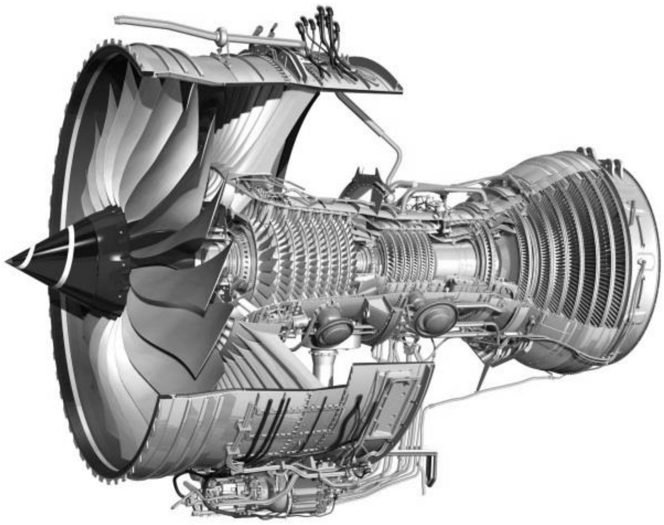


Figure 1-1 Trent 1000 gas turbine engine ©Rolls-Royce plc.

Rolls-Royce plc is thus an informative environment in which to explore the relationship between engineering design and measurement technology.

1.3 Research scope

The scope has been aligned to take advantage of the environment in which the research was conducted and encompasses the following:

- Manufacturing

  The research is taking place within a manufacturing context; measurement-related topics within product development, service, and repair are out of scope.

  From a manufacturing perspective, dimensional metrology issues become most relevant during the product definition stage of engineering design, when allowable deviations are annotated on engineering drawings or models.

- Components

  The emphasis of the research is on components, as opposed to higher-level systems such as assemblies or engine modules. It is reasoned that for complex mechanical systems of the type that Rolls-Royce plc produce, much of the variety that is found at a system level is created by variation of components (Whitney, 2003).

- Dimensional metrology

  Components have many properties that can be measured in order to determine whether they will function according to the intent of the design. The properties can be categorised as static, dynamic, or physical (Zhao, Brown, et al., 2011, pp. 1–2). Static properties include size and shape, and are referred to under the heading of dimensional metrology. Dynamic properties, such as the texture of a surface, may be grouped under the banner of surface metrology. Finally, physical metrology deals with the physical and chemical condition of a component. For a component to function, all three of these types of properties must be satisfactory. However, this research is concentrated on the measurement of the static properties: size, location, orientation, and form, as shaded on Figure 1-2 (adapted from Henzold, 2006, p. 1).

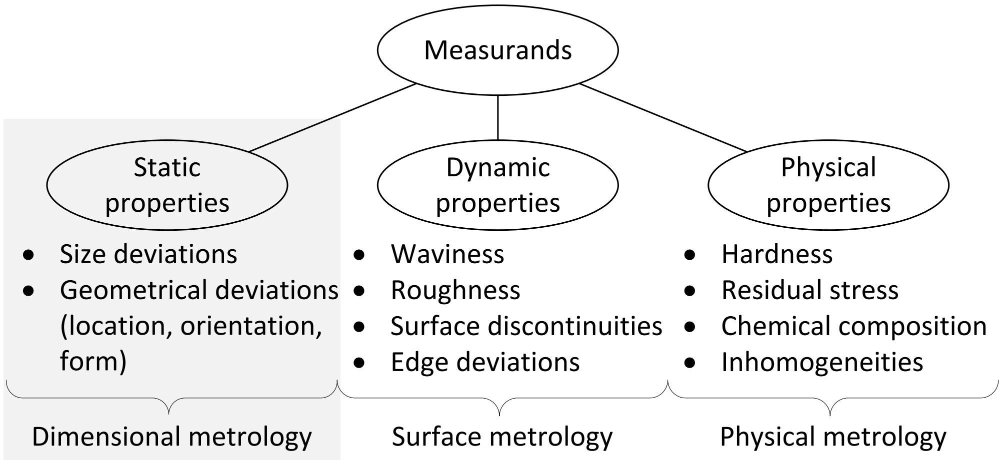


Figure 1-2 Properties of a component that could be measured.

- Coordinate measuring machines

  A mature measuring technology, known as the coordinate measuring machine (CMM), has been selected as a focal point for the investigation. CMMs have been selected since they continue to dominate the aerospace industry over fifty years after their invention. Whilst other measurement techniques, such as non-contact portable devices are growing in popularity, it is widely commented that CMMs are likely to have an important role within manufacturing for many years to come. Thus, this is where the research is expected to have a high impact and the greatest likelihood of success.

- High-precision aerospace

  In order to maximise the value of the research to the industrial sponsor, components and tolerances used within aerospace engines were targeted. Since this covers a wide-range of high precision components of differing geometry and scales (as visualised in Figure 1-1), it is expected that findings from the research will have a wide application within industry. Related to this, the focus will be on components produced through conventional subtractive technologies; additive manufacture will not be considered.

1.4 Research assumptions

The research is premised on the following two assumptions:

1. There is significant value in reducing unmeasurables for the stakeholders of the research;
2. PLM is a suitable tool to support efforts in reducing unmeasurables.

In order to validate these assumptions, two exploratory case studies were carried out, as summarised below.

1.4.1 Exploratory case 1: Robust multidisciplinary design optimisation

The first case study is concerned with the design and manufacture of turbine blades. Turbine blades are one of the most challenging components to design, manufacture, and measure in a gas turbine engine (Beale, 2012). The design is optimised through a semi-automated process that is orchestrated through a PLM system. The process allows for fast design iterations and robust optimisation, taking into account knowledge from skill disciplines that include aerodynamics, thermal, stress, manufacturing, and cost analysis. In this design process, the measurement of geometry is considered indirectly, from within a manufacturing context. The potential benefits of promoting the importance of measurement were therefore explored, in order that engineering design parameters could be more directly related to the quality, cost, and feasibility of measurement technology.

A group modelling workshop and semi-structured interviews were held with staff from design, manufacturing, and measurement disciplines. Following an analysis of the model and interview data, it was concluded that measurement and engineering design should work closer together in order to cultivate the following three categories of knowledge types, which are considered further in this thesis:

- Standardisation of measurement methods

  Value can be extracted if *what* knowledge to reuse and *how* to reuse it is better understood and managed. For example, if the ability to use a specific measuring system is best in class, then one might minimise risk to other parts of manufacturing by reusing this knowledge instead of exploiting newer opportunities.

- Manufacturing process understanding

  Manufacturing engineers need to know what systems to buy or develop, and how they can use measurement knowledge to improve manufacturing process knowledge, with the ultimate objective of reducing the cost of final inspection.

- Novelty

  A knowledge type was found for distinguishing novelty and how this affects manufacturability. A lack of appreciation of this knowledge type could hinder advancement in two ways: Firstly, measurement engineers might depend on reusing existing knowledge, and therefore not explore other opportunities; secondly, design engineers might not cater for the complexity of the measurement, thereby making it difficult to manufacture.

Further details of this study are in Saunders, Giudice, et al. (2014).

1.4.2 Exploratory case 2: Feature verification risk analysis

During the course of the research, it was found that practitioners frequently argued that there is already adequate mitigation against unmeasurables through a process that is known within Rolls-Royce plc as feature verification risk assessment (FVRA). The process was introduced to ensure that design for manufacture reviews are carried out in a systematic way, feature-by-feature, when products are introduced into manufacturing. FVRA is an application of failure mode effects and criticality analysis (FMECA) (ISO 60812, 2006). Each geometric specification is scored with respect to its design criticality, manufacturability, and the ability for size and geometric deviations to be detected through measurement. In this way, the design and manufacturing teams are brought together to identify critical areas that could prove problematic for verification.

In order to explore FVRA as a potential solution for tackling unmeasurables, the researcher observed the process. The case study concerned planning for the reintroduction of a compressor stator for a helicopter engine into manufacturing at Rolls-Royce plc. The engineering drawings for this component were issued in 1999, though the design had evolved from a previous product, so the origins of the features and associated drawing definition could be several decades old.

Feature verification risk assessment comprises the following steps:

- Feature identification

  First, each geometric specification is assigned an identity number, and is now known as a feature. The relevant nominal and tolerance data are then recorded. For the case of the component under study, there were one hundred and eighty-two features on three drawing sheets; however, it is not unknown to have nearer to one thousand features, and there may sometimes be thirty or more sheets to define a single component.

- Assignment of severity, occurrence, and detection scores

  Having recorded all the features, a discussion is held between design, manufacturing, and measurement representatives to agree a score between one and ten for severity, (where one implies the consequence of non-conformance is not severe to design), occurrence (where one implies non-conformance is unlikely to occur), and detection (where one implies that non-conformance is easily detectable - ten would be an indicator of an unmeasurable). These three numbers are multiplied together to calculate a risk priority number. A worked example is provided in Section 8.3.2.

- Verification risk assessment

  Following one or more workshops to agree these scores, the most critical features will have been highlighted. Efforts should be made to reduce risk priority numbers where practicable - indeed, company procedures advise that the process cannot be exited until all features have a risk priority number of less than five hundred. Additionally, there should be no features with an occurrence of ten.

Two workshops were held for the compressor stator. The observer was present for the second session, in which eighty-one features were reviewed. Present were two representatives from measurement, one manufacturing engineer, and three designers. The session lasted for four hours, representing eighteen minutes of effort per feature, when considering that there were six active participants. Overall, five features (six per cent of the total) were identified with a risk priority number greater than five hundred, and therefore required further investigation.

The case study demonstrated how feature verification risk assessment can help to reduce the risk of unmeasurables through a systematic and interdisciplinary way of working. However, in this instance it was observed that the process required significant effort, occurred at a late stage in the manufacturing process development, and was isolated from PLM. In particular, it was noticeable that the measurement representatives lacked the tools to communicate the costs involved in measurement, as compared with design and manufacturing representatives – thus much use had to be made of expert judgement.

1.5 Research question

In view of the motivation, environment, and scope of the study, the research question has been worded to allow for a holistic examination of how design intent is translated to a CMM task within the context of manufacturing. The question stresses the need to migrate as much of the process as feasible from a physical to digital environment, whilst recognising the need to build on available proven technology in order to meet the stakeholder requirements:

> *How feasible is it, using available technology, to fully plan dimensional measurement processes for coordinate measuring machines in a digital environment without conducting physical trials?*

1.6 Thesis structure

Referring to Figure 1-3 the thesis has begun with an assessment of the stakeholder requirements which have been validated through exploratory case studies. This has led to the main research question, as identified in Section 1.5.

The literature and state of art are reviewed in Chapter 2 with the purpose of identifying knowledge and technology gaps. Chapter 3 then develops the research design which will be used to support the study of these areas, and results in the sub-questions and objectives for the EngD.

The main research activities are described in four inter-related chapters. The research in the chapters on the left of Figure 1-3 was carried out in a laboratory environment, whilst the research for the chapters on the right took place in an industrial setting. Firstly, a framework is developed in Chapter 4 in order to locate and better understand existing systems solutions; secondly, in Chapter 5, the technology and standards required to link design and measurement are investigated through a series of interventions. Building on the findings from Chapter 4 and Chapter 5, Chapter 6 offers an example of a solution that formally integrates the engineering design system to measurement technology. Fourthly, in Chapter 7, the potential route to deployment is considered.

Finally, in the remaining two chapters, the contribution, limitations, and options for further study are identified.

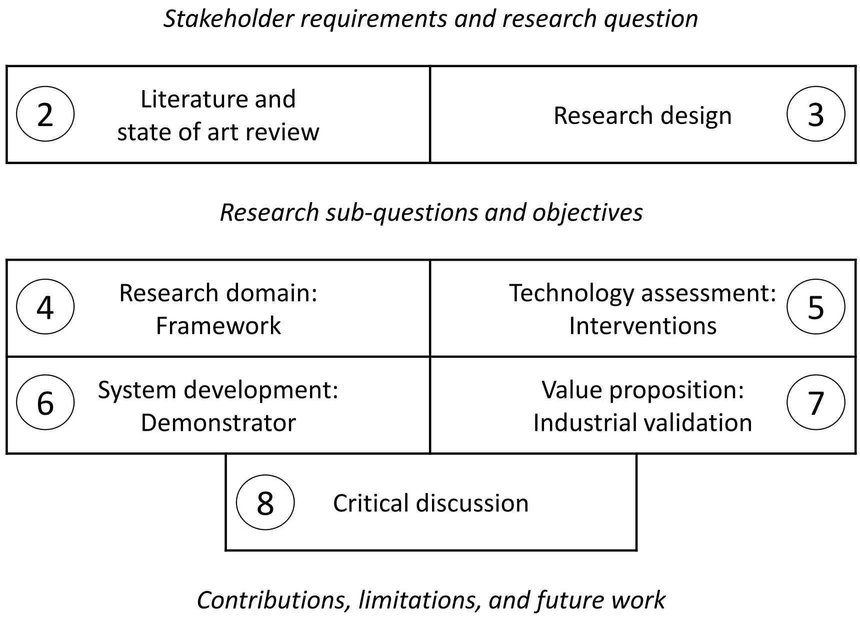


Figure 1-3 Chapter plan.

1.7 Summary

This chapter of the thesis has introduced the motivation for the research, the environment in which it has been conducted, a high-level overview of the research boundaries, some example issues, and the research question to be addressed; an outline structure for the thesis was also provided. The next section will review extant research and state of art in this area.

Chapter 2 Literature and state of art review

2.1 Introduction

In Chapter 1, the problem was introduced; features may be designed that are not feasible or are unreasonably costly to measure – such features have been termed 'unmeasurables'. Exploratory studies were undertaken to test the belief that the incidence of unmeasurables could be reduced by giving measurement a stronger voice in the design process, at least within the context of manufacturing at Rolls-Royce plc. The main research question was developed accordingly:

> *How feasible is it, using available technology, to fully plan dimensional measurement processes for coordinate measuring machines in a digital environment without conducting physical trials?*

The purpose of this chapter is to review the literature and state of art in order to identify knowledge gaps. To achieve this, the review has been structured around the following topics:

- How have engineering design and measurement technology evolved together in the past? (Section 2.2)
- How is geometry specified today? (Section 2.3)
- What are the primary considerations for employing measurement technology to verify geometry in a traceable way, with specific consideration to CMM systems? (Section 2.4)
- What conceptual frameworks already exist to link design and measurement? (Section 2.5)
- What is the state of art for managing measurement knowledge in PLM? (Section 2.6)

2.2 Historical perspective

> *How have engineering design and measurement technology evolved together in the past?*

The major milestones in the relationship between engineering design and measurement technology up until 1997 were summarised in Voelcker (1998). Voelcker suggests that there have been three eras in the history of mechanical engineering, which he terms 'mechanisation', 'proliferation', and 'automation', as shown in the top portions of Figure 2-1. This diagram has been adapted and extended from a figure in Voelcker (1998); the milestones have been grouped to show whether they relate to engineering design (such as 'algebraic geometry'), or the measurement technology that is employed to detect geometric variation during manufacturing (such as 'proportional divider').

Mechanisation is the period in which machines began to replace human power, which is a process that began in ancient times. Before mechanisation, the dimensions of components would be adjusted by highly skilled craftsmen in order to achieve the required type of fit. As machines became more widely used, engineers began to draft designs on drawings, and functional gauges, such as a plug to verify the size of a hole, were used for inspection.

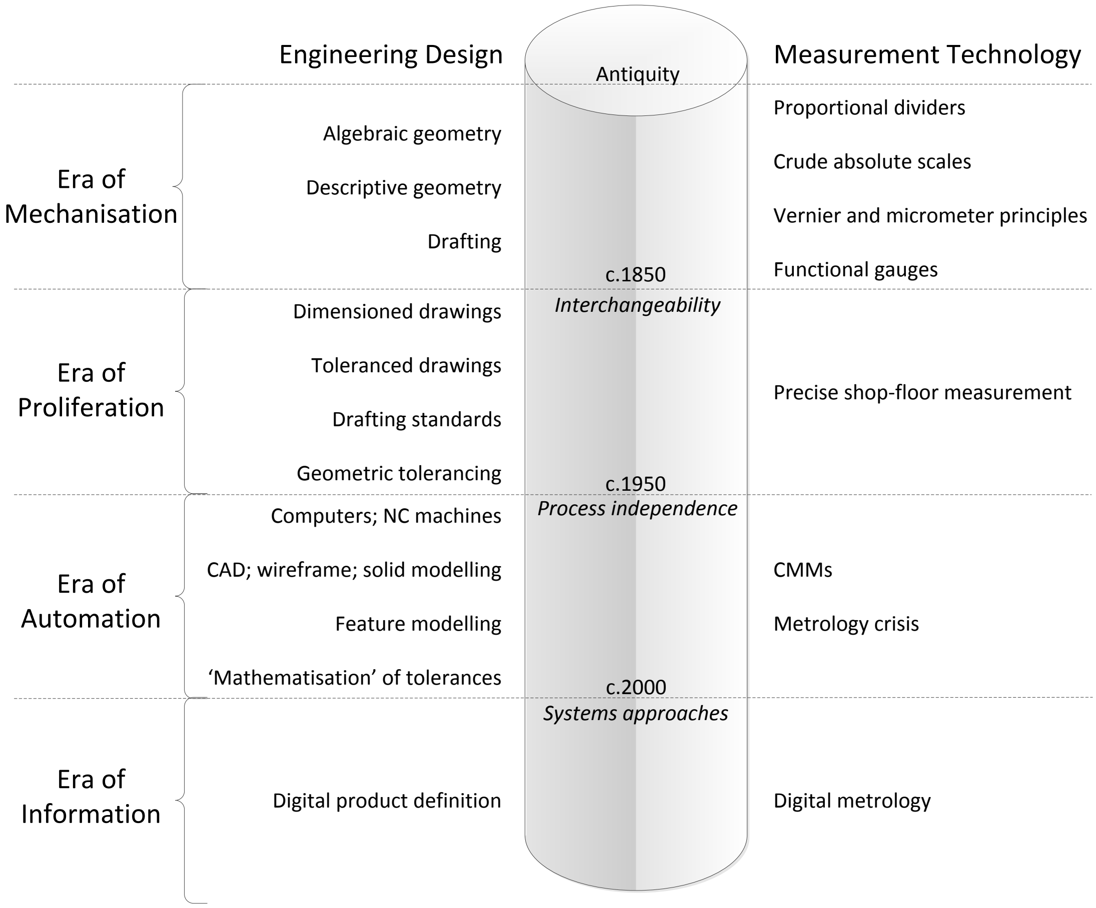


Figure 2-1 Historical perspective on design and measurement.

However, Voelker notes that it was not until around 1850 that dimensions were put on drawings, and this was driven partly by the affordability of measurement tools such as micrometers and calipers; tolerances did not appear until the end of the nineteenth century.

Mechanisation gradually transitioned to proliferation, when increasing numbers of products were made in batch or mass production from around the middle of the nineteenth century. As products began to proliferate, so too did manufacturing processes; components were no longer necessarily designed and manufactured in a single location. It was found that toleranced drawings contained ambiguities, and a better means of communication was required. In some cases manufacturing operations could be found as 'process callouts' on the drawing – for example, a grinding operation might be explicitly specified instead of the required tolerance. This practice caused problems in the supply chain with manufacturers who had differing machining capabilities. As a result, by the middle of the twentieth century it was recognised good practice to avoid such process callouts in favour of 'process independence'. This paved the way towards the development of geometric dimensioning and tolerancing (GD&T), which is a symbolic language that is used to communicate the intended geometry of parts and their allowable deviations.

The middle of the twentieth century marks the start of the era of automation, where specialist machines were replaced by more versatile devices. At this time, parallel innovations within the engineering design and coordinate metrology communities ensured a high degree of process independence. For example, design was facilitated by the introduction of computer-aided design (CAD) which started to become mainstream from 1969 (Weisberg, 2008, pp. 2–9); standards for solid modelling were introduced in 1980, through the publication of the initial graphics exchange specification, and; interoperability standards made their debut in 1984 with the first standard for the exchange of product model data. Meanwhile, CMMs enjoyed a rapid uptake following the invention of the 3D touch trigger probe in 1973 (McMurtry, 1997), making them an affordable alternative to the use of a multitude of precision tools for first principle measurements.

1988 saw the beginnings of a 'metrology crisis' when it was found that some CMM systems reported results incorrectly against the design specification (Walker, 1988). The crisis led to an increased focus on computational metrology (as reported in Srinivasan, 2013), at a time when tolerance specifications were also being addressed so that they might be built on a sounder scientific basis. Thus, mathematical rigour was extended to geometric tolerancing with the publication of documents such as the ASME Y14.5.1M (1994) 'math standard', whilst urgent attention was made to improve and validate the algorithms used within CMMs (e.g. Hopp, 1993).

With the benefit of hindsight, it could be argued that Voelcker was writing around the start of a new 'era of information'. The increasing availability of networked personal computers allowed organisations to more fully explore the opportunities available from bringing processes together through digital enterprise technology, where digital enterprise technology is defined as 'the collection of systems and methods for the digital modelling of the global product development and realization process in the context of lifecycle management' (Maropoulos, 2003). It was also around this time that Eppinger (2001) wrote 'the exchange of information is the lifeblood of product development'.

Digital enterprise technology has affected engineering design and measurement technology significantly, not least through the increasing digitisation of product definition and metrology:

- Digital product definition

  The way in which geometric details are specified in design (the 'product definition') has been gradually transitioning from a 2D to 3D paradigm (Aberdeen Group, 2006). When dimensions and tolerances are *semantically* linked to geometric features in 3D engineering models, this can be considered as a digital product definition. Whilst the trend towards digital product definition began almost as far back as when CAD was introduced to industry, it is only in recent years that computing power has been sufficient to contemplate allowing such fully-defined 3D models to proliferate through supply chains (Stark, 2011, pp. 23–26).

- Digital computational metrology

  Measurement technology has also undergone significant change, resulting in a step change in the quantity of measurement data that needs to be managed, as well as the ability to analyse and make sense of it (ISO/TC 213, 2012). CMMs have grown in popularity, and large numbers of measurement points can now be collected through recently-developed scanning or photogrammetry techniques which can be integrated in multi-sensor systems (see reviews in Cristoph and Neumann, 2012; Weckenmann et al., 2004).

Finally, it may be observed that it is around the year 2001 that PLM emerged as a potential mediator between engineering design and measurement technology in this increasingly digital environment (Stark, 2011, pp. 65–79).

2.3 Product specification

How is geometry specified today?

In the present-day digital environment it is essential that the geometric requirements provided by engineering design are specified precisely and unambiguously (Frechette, 2011). Likewise, the measurement technology that is deployed to verify those requirements needs to be utilised efficiently and effectively.

Standards are important in such an environment (Lubell et al., 2012, pp. 3–7), and fortunately engineering design and dimensional metrology are mature domains that are the subject of a large number of standards. For example, ISO/TC 213, that is the ISO committee responsible for standards in dimensional and geometrical product specifications and verification, maintain over one hundred and fifty international standards – many of which pertain to the relationship between engineering design and measurement technology.

2.3.1 Geometric dimensioning and tolerancing

The design data that specifies what needs to be measured is most typically modelled using GD&T. As the name suggests, GD&T actually covers two areas of tolerancing: Geometrical, which is concerned with form, location, and orientation; and dimensioning, which is concerned with controlling size (Green, 2005, pp. 3–5). A succinct definition of GD&T is given by McGee (2011), who explains: ‘it defines the orientation of the part for measurement. It defines all the lines associated with the measurement. It totally defines the shape of the part.’ An example of GD&T is shown in Figure 2-2.

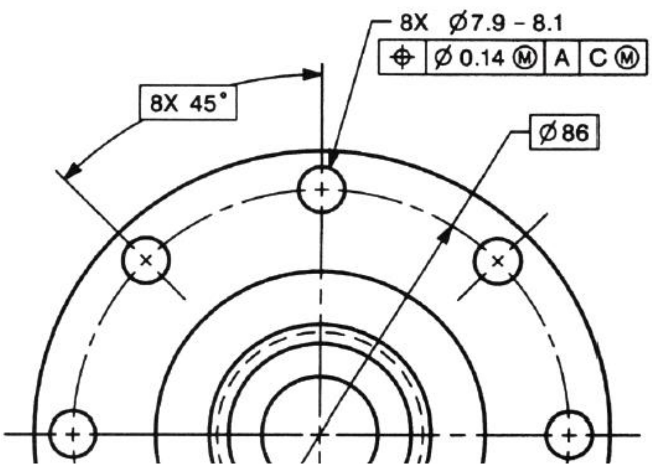
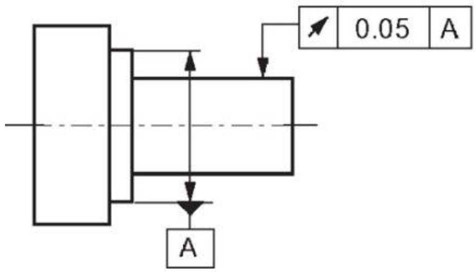


Figure 2-2 Geometric dimensioning and tolerancing example (ASME Y14.5, 2009).

Henzold (2006, pp. 255–263) categorises GD&T into function-, manufacturing-, and inspection-related. He advises that if you rely only on function-related GD&T (which depends only on design), it may be necessary to create further specifications with manufacturing- and/or inspection-related GD&T. Alternatively, the drawing may need modification. In other words, there may be an 'optimum' GD&T that requires input from all relevant skill disciplines, including measurement. The example in Figure 2-3 (from Henzold, 2006, p. 259) shows an example of why GD&T information may need to be sensitive to the needs of all users; in this case, the right hand version could be said to be more 'inspection-related' than the left hand version, which has a very short datum.



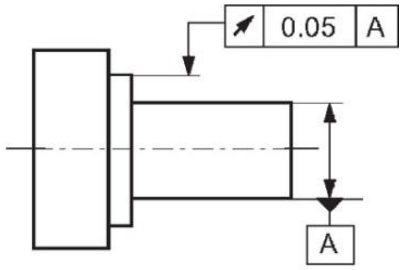


Figure 2-3 Tolerancing: Inspection appropriate (right) and inappropriate (left).

The generation of optimum GD&T appears to be an area lacking in substantial research. For example, the specification of tolerances are an important consideration in GD&T; however, in a thorough review of research in tolerancing, Hong and Chang (2002) found that tolerance specification was the least studied area, and there is no evidence that the situation has changed over the last decade, according to Krogstie and Martinsen (2013). Nonetheless, some attempts to generate optimum GD&T can be identified in the literature. For instance, Cristofolini et al. (2009) identify that there is a gap in this area, observing that although there is a well-studied field known as 'design for verification' in the electronic and software industry, there is little emphasis on considering verification process characteristics in the field of mechanical engineering and design. They suggest the use of a knowledge-based system that they call 'design guidelines'. Design guidelines are an attempt to describe the relationship between product features once a measurement process has been specified. In the example provided in Cristofolini et al. (2009), it is known that a specific CMM will be used to measure a given component, and so recommendations are made to orient the part and change the type of probe that had been originally considered. In other cases, it is expected that design guidelines might advise changes to the design – for example, adding flat surfaces, or increasing the size of a cavity in order to permit access for a measuring probe.

Automated approaches have also been developed; for example, software tools have been created to check the validity of GD&T with respect to measurability (Brown, 2000); this may include rules such as insisting on a radius of greater than ninety degrees before permitting the use of the radius control. It is expected that such tools could be further developed to automatically generate aspects of the GD&T. However, advice can be contradictory. The standards and practitioners tend to promote the concept of function-related GD&T with associated manufacturing and inspection schemes, yet in many industrial situations it is uncommon to find additional inspection-related GD&T schemes. For example, on discussing this topic with experts at Rolls-Royce plc, it was noted that it is rare to find a separate GD&T drawing for inspection purposes; however, within manufacturing, there may be a 'datum story' that is required to allow operations to take place when a referenced datum has not yet been produced.

GD&T standards have been widely adopted in industry (Srinivasan, 2008). Whilst there are several competing GD&T standards, they are dominated by the international standard Geometrical Product Specification (GPS), and the US standard ASME Y14.5 (Krulikowski and DeRaad, 1999). There are discrepancies between the ISO GPS and ASME Y14.5 standards (Henzold, 2006; Humienny, 2009). A well-known example is that of the envelope principle which states that form error should be included when evaluating size. In ASME Y14.5, the envelope principle is the default, whereas ISO GPS defaults to the principle of independence, where form and size are evaluated individually. It has been stated that there is an ambition amongst both the ISO and ASME communities to harmonise standards (Srinivasan, 2013). Yet this view is not unanimous, and it seems unlikely that the ISO GPS and ASME Y14.5 standards will be harmonised in the near future. For instance, the most recent attempt within the organisations to understand the differences between the two systems has petered out, although some general comparisons are available (ISO/TC 213, 2010). It should also be noted that even should harmonisation take place, the landscape is complicated by the fact that in practice, there are typically more than one version of the same standard in circulation at any one time (e.g. ASME Y14.5M, 1994, and ASME Y14.5, 2009), and organizations may choose to supplement or amend standards to make them more appropriate to their needs (Krulikowski and DeRaad, 1999, pp. 6/28–29).

Furthermore, one might question the general level of expertise that users of these standards have when observing the range of discussion forums on the topic, or training courses available. The standards have become successively complex over time. They are still typically described using examples, rather than prescriptive rules, which mean that they can be open to interpretation (Nielsen, 2013). Because of this, some organisations have sought to invoke additional rules (Tandler, 2008) or only use a subset of GD&T (Hetland, 2010). Even subject matter experts can find the standards challenging to interpret. For example, in Orchard (2011a), the speaker posed questions about the meaning of terminology in ASME Y14.5M (1994) to an expert audience containing GD&T specialists and contributors to the standards; however, no satisfactory answers were given.

2.3.2 Product and manufacturing information

The way in which GD&T is produced and used is changing as a result of the need to apply it to 3D models. The term 'product and manufacturing information' (PMI) is often employed in this context. PMI actually includes additional information such as surface texture specifications, finish requirements, process notes, material specifications, and welding symbols (Frechette et al., 2013), though for the purpose of measurement planning on CMMs, it is the GD&T element which is most important. An example of PMI is shown in Figure 2-4.

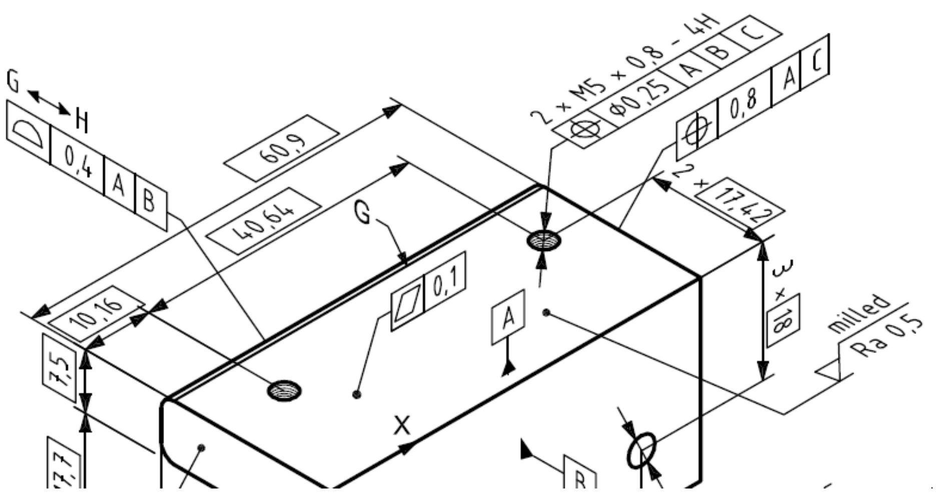


Figure 2-4 PMI example (ISO/DIS 16792, 2012).

The ISO and ASME standards that describe the rules for applying PMI are known as ASME Y14.41 (2012) and ISO 16792 (2012), the latter of which is in draft form and targeted to update the current 2006 version in 2015. The standards are new, and models have only recently been released for interoperability testing (Frechette et al., 2013). Indeed, many organisations today operate using a combination of 2D and 3D dimensional and geometric tolerances; even when 3D tolerances are employed, their use can range from a simple description of the envelope dimensions, through to a fully toleranced model with a number of possible permutations in between (Pippenger, 2013; Quintana et al., 2010).

Some researchers have developed methods to supplement PMI with functional requirements (Weckenmann and Hartmann, 2013); nonetheless, the annotation of drawings, using systems that are rooted in a pre-digital GD&T age, is deeply embedded into the current system of manufacturing and it seems unlikely that it would be usurped for several decades (Srinivasan, 2008).

2.4 Product verification

What are the primary considerations for employing measurement technology to verify geometry in a traceable way, with specific consideration to CMM systems?

In order to demonstrate that the geometric requirements specified through GD&T or PMI have been met, objective evidence through measurement is normally required. The process is known as 'verification' (JCGM 200, 2008), and the quantity intended to be measured (in this case a GD&T or PMI requirement) is known as the 'measurand' (JCGM 200, 2008).

Standards are fundamental within product verification, just as they are for product specification. Central amongst the standards in measurement is the *International vocabulary of metrology* (VIM) (JCGM 200, 2008). This standard was developed by the Joint Committee for Guides in Metrology under the auspices of the International Bureau of Weights and Measures. The Joint Committee for Guides in Metrology is also responsible for the *Guide to the Expression of Uncertainty in Measurement* (GUM) (JCGM 100, 2008) which gives direction on how to evaluate and express measurement uncertainty.

2.4.1 Measurement uncertainty and conformance rules

No measurement can be perfect which means that the information provided about the measurand during verification is always incomplete. In order to enhance the utility of the information provided by measurement, one might provide a probability that the reported value is correct to within a stated interval. Doiron (1997) provides a colourful example of the researcher who is reputed to have declared:

> *We think our reported value is good to one part in ten thousand: we are willing to bet our own money at even odds that it is correct to two parts in ten thousand. Furthermore, if by any chance our value is shown to be in error by more than one part in one thousand, we are prepared to eat the apparatus and drink the ammonia.*

The above statement is an example of expressing a 'measurement uncertainty'. In fact, uncertainty is a central concept when considering the role of measurement in product verification. The term can be traced back at least as far as 1889 when the first international prototype metre and its national copies were established during a conference at the International Bureau of Weights and Measures. A suggestion was made to include the phrase 'with a probable error that does not exceed 0.0002 mm' with the certificates that were to accompany the first national prototypes, and the word 'incertitude' (French for 'uncertainty') was used during this meeting. However, the proposal was quashed at the time on the grounds that such uncertainty statements would be hard to defend (Quinn, 2011, p. 143).

Measurement uncertainty is contemporarily defined in the VIM as a 'non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used' (JCGM 200, 2008). The VIM reinforces the need to understand measurement uncertainty by stating that measurement results should include 'relevant information', advising that this information is often a measurement uncertainty. In fact, according to the VIM, measurement uncertainty should only be excluded from the results when it is considered negligible for its intended use.

Since a value for measurement uncertainty itself cannot be precisely known either, it is recommended that a measurement uncertainty 'statement' is provided that includes the following information (Bell, 1999):

- The measurement result and its associated uncertainty;
- The level of confidence that can be attributed to the uncertainty;
- The method used to estimate uncertainty.

In such a statement, the uncertainty is quantified as the interval over which it is valid. More fully described as 'expanded uncertainty', U, it is a multiple of the 'standard uncertainty', u, where standard uncertainty is expressed as a standard deviation (JCGM 200, 2008).[1] Standard uncertainty is converted to expanded uncertainty through a coverage factor, k, as shown in equation [2-1]. The level of

[1] Though not recommended in the GUM, the term 'expanded uncertainty' may sometimes include a correction for known systematic effects, b, that has not been included with the measurement result.

confidence attributed to the expanded uncertainty thus depends on the type of probability distribution of the quantity being reported, and the coverage factor.

$$U = k \times u \qquad [2\text{-}1]$$

An example pertaining to the flatness tolerance of datum A in Figure 2-4 might be: 'The flatness of surface 'A' was 0.074 mm ± 0.02 mm. The reported uncertainty is based on a coverage factor k = 2, providing a level of confidence of approximately 95 %. The uncertainty was estimated according to company procedure ABC.'

In this example, it is clear that the information about uncertainty is of crucial importance in order to make a decision as to whether the measurand is within tolerance. Had the reported uncertainty been 0.03 mm, it would be possible to argue that the result is marginal (since 0.074 mm + 0.03 mm is greater than the 0.1 mm allowable deviation according to the tolerance specification); thus there could be grounds for rejecting the component. Such rules are known as 'decision rules' in the standards (ASME B89.7.3.1, 2001; ISO 14253-1, 2013). The default decision rule in the ISO system is that the specification zone must be reduced by the value of measurement uncertainty in order to assess conformance (ISO 14253-1, 2013). ASME provides more flexibility by allowing producers and consumer to agree on a proportion of uncertainty that will be included in the decision-making criteria (ASME B89.7.3.1, 2001).

2.4.2 Metrological traceability

In addition to the requirement for making better conformance decisions, measurement uncertainty is needed in order to demonstrate metrological traceability. Traceability, as illustrated in Figure 2-5 (adapted and extended from a figure in ASME B89.7.5, 2006), is in turn theoretically necessary in order to meet ISO 9001 (2008) quality management standards and the associated guidance on developing measurement management systems in ISO 10012 (2003). Metrological traceability is defined as the 'property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty' (JCGM 200, 2008). The strengths and limitations of this definition in an industrial context are discussed in a foreword to an ASME technical report *Metrological Traceability of Dimensional Measurements to the SI Unit of Length* (ASME B89.7.5, 2006).

The report notes that the definition of traceability is the subject of considerable confusion within industry. Firstly, there is debate as to what constitutes an appropriate terminus for a reference standard; should this be an international standard, or is a calibration certificate sufficient? Secondly, it is unclear which factors should be included in the chain of calibrations, as there can be a multitude of influence quantities when verifying geometric measurements which could make the chain of calibrations prohibitively complicated. Thirdly, when uncertainty is calculated using the methods outlined in the GUM, 'expert judgement' is permitted within the uncertainty budget; one might therefore question how the mind of an expert can adequately be captured within a traceability statement. ASME B89.7.5 goes on to make the case for a pragmatic approach to demonstrating traceability, where the effort required for proving traceability for each uncertainty component is balanced with its overall estimated contribution to uncertainty.

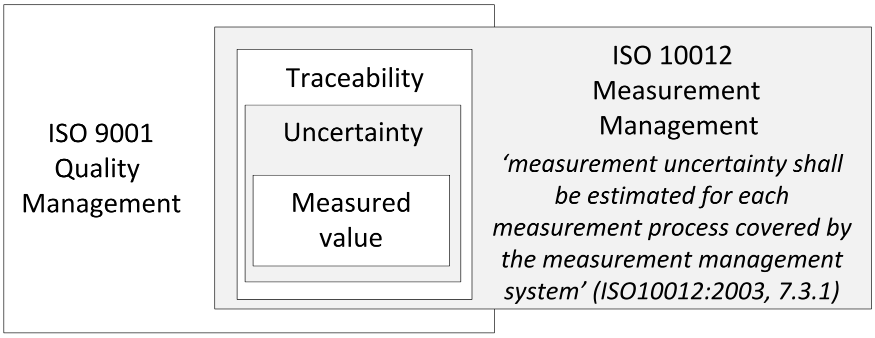


Figure 2-5 Requirements for measurement uncertainty within ISO standards.

The case for a 'fit for purpose' approach to uncertainty evaluation is also hinted at within ISO 10012, which states that although measurement uncertainty should be estimated for all the measurement processes in scope of a measurement management system, the effort devoted to this task should be 'commensurate with the importance of the measurement results to the quality of the organization' (ISO 10012, 2003).

2.4.3 Sources of errors on CMM systems

Knowledge of uncertainty can therefore be as critical as the measured quantity value itself, and ideally one would know the uncertainty associated with every measurement that is reported for accurate decision making and to facilitate traceability. This is challenging for CMM systems where there are a multitude of error sources to be considered, and it may be unclear as to their relative contribution to measurement uncertainty. The categorisation given by Wilhelm et al. (2001) is widely used in the literature; this source groups uncertainty contributors for CMM systems into five categories, as shown in Figure 2-6; these are hardware, workpiece, sampling strategy, algorithms, and extrinsic factors.

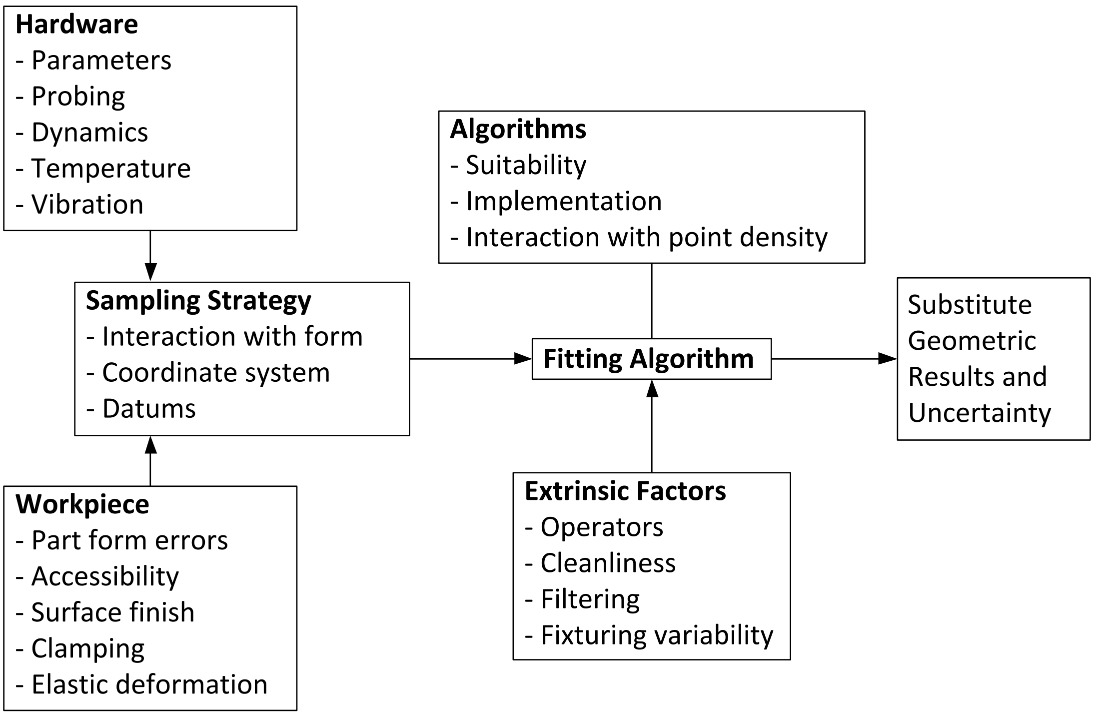


Figure 2-6 CMM system uncertainty contributors (Wilhelm et al., 2001)**.**

- Hardware

  Hardware sources include errors associated with the CMM structure, some of which can be quite specific to the design. For example, it has been demonstrated that introducing a heavy load onto a CMM can have quite different impacts depending on the CMM type (Phillips, 2012, p. 211).

  Probing errors may be introduced depending on factors such as the ball size and material, the stylus length and stiffness, any extensions that are used, and their orientation during measurement (Chan et al., 1997).

  Dynamic effects could be particularly significant for large CMMs, or when scanning probes are used along curved paths (Phillips, 2012, p. 213).

  Furthermore, in industrial settings CMMs may be situated in thermal environments that are outside the manufacturer's recommended temperature ranges, and one might expect vibration to be a potential issue.

- Workpiece

  The workpiece itself can also introduce errors. No manufactured part is perfect, but when it is measured a nominal geometry must be assumed for the purpose of programming. This has the potential to introduce errors if the vector from the surface to the probe centre is incorrectly evaluated (as discussed in Ristic et al., 2001).

  Other workpiece-dependent factors such as the surface finish of the part, the method of clamping and any deformation also influence measurement results.

- Sampling strategy

  Sampling strategy involves decisions around the number and location of measurement points or scan paths. The optimal choice is highly dependent on the interaction with form (Barari and Mordo, 2013; Edgeworth and Wilhelm, 1999; Weckenmann and Knauer, 1999).

- Algorithms

  The latest standards used to specify geometric requirements provide the facility to specify the fitting algorithms that should be used; for example, least squares, maximum inscribed, or minimum circumscribed modifiers can be associated with the specification of a circle (Morse and Srinivasan, 2013). However, it remains to be seen how widely these standards will be adopted.

- Extrinsic factors

  Finally, extrinsic factors need to be considered, which cover elements such as cleanliness, or variation in fixturing procedures.

Because of the strong interaction between the measurement task being performed on a CMM and the uncertainty result that is achieved, Wilhelm et al. (2001) introduced the phrase 'task-specific uncertainty', emphasising the need to evaluate each measurement task separately.

2.4.4 Methods for evaluating CMM task-specific uncertainty

Three methods for evaluating task-specific measurement uncertainty on CMMs are outlined in ISO 15530-1 (2013); they may be used singly or in combination.

- Sensitivity analysis

  The first of the methods is known as sensitivity analysis and is described in the GUM (JCGM 100, 2008). In sensitivity analysis, measurement uncertainty is estimated through a two-stage process. First, the problem is formulated in metrological terms; second, a computation is performed. During formulation, a measurement model is developed in which the measurand to be estimated is related to the input quantities on which it depends. Probability density functions (PDF) are assigned to those input quantities. In the computation stage, the probability densities are propagated through the measurement model in order to generate a probability density function for the output quantity. The model requires information about the relative influence of each input quantity on the output quantity, in the form of sensitivity coefficients and correlations between the inputs. The process is illustrated in Figure 2-7.

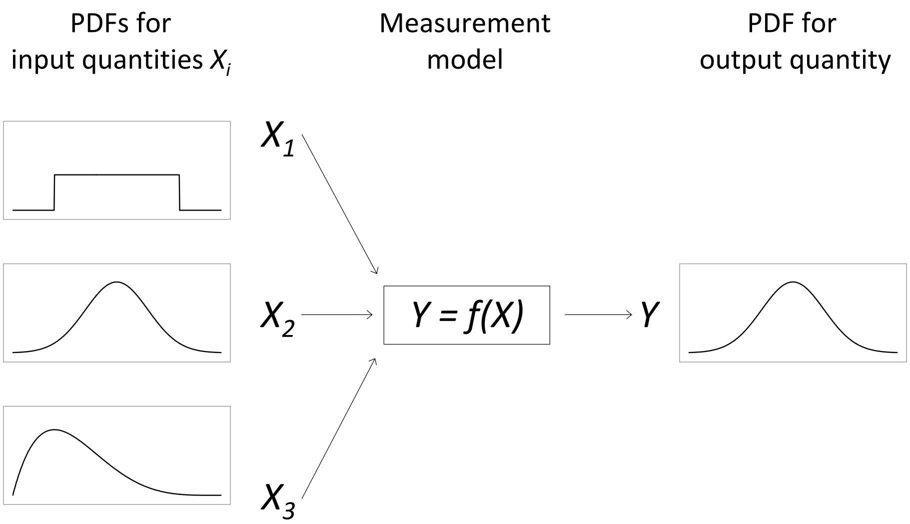


Figure 2-7 Propagation of probability densities in GUM.

  Sensitivity analysis requires a comprehensive understanding of the uncertainty sources and a suitable mathematical model. Most researchers regard it as rigorous, though hard to achieve in all but the most simple cases (Flack, 2013; Kruth et al., 2009). This assertion has recently been challenged by a group who have developed software that implements sensitivity analysis for CMM tasks for a variety of prismatic features (Jakubiec et al., 2012). The results are promising, although since it is new, it has not been independently validated or gained wide acceptance in the CMM community.

- Comparative approach

  The second method referred to in ISO 15530-1 (2013) is a comparative approach that involves the use of a comparable artefact to capture uncertainty sources and interactions (ISO 15530-3, 2011); it is also regarded as rigorous and defensible, though can be costly as it relies on the existence of an artefact, the availability of a more capable measuring system, and the ability to meet similarity conditions (Flack, 2013).

- Monte Carlo based simulation

The third method is to use Monte Carlo based simulation known as uncertainty evaluating software (UES) (ISO/TS 15530-4, 2008). UES systems can be broadly grouped into two categories according to how input data is collected.

The first type of UES is closely integrated with a specific CMM; a comprehensive model of the CMM is developed, typically by the CMM manufacturer when commissioning the software. During measurement, further inputs may be acquired, for example through a special probe qualification routine and gathering temperature data (Trapet et al., 1999).

The second type of UES was developed to allow for the case when less complete information is available. For example, one may only have machine performance data in the form of a calibration report. To deal with this case a method that has been labelled 'simulation by constraints' was invented (Phillips et al., 1997). This method makes the assumption that points near to each other should have similar errors.

The concept of simulation by constraints is shown in Figure 2-8, whilst the two types of UES can usefully be regarded as lying along a continuum of simulation methods, as shown schematically in Figure 2-9. Both figures are adapted from Phillips et al. (1997)

As for any simulation, there will always be factors that UES does not consider, and consequently it can only provide an estimate for part of the total measurement uncertainty. ISO 15530-4 (2008) provides a useful checklist of considerations. Thus it may be advisable to use simulation in combination with other techniques (Phillips, 2012, pp. 255–265).

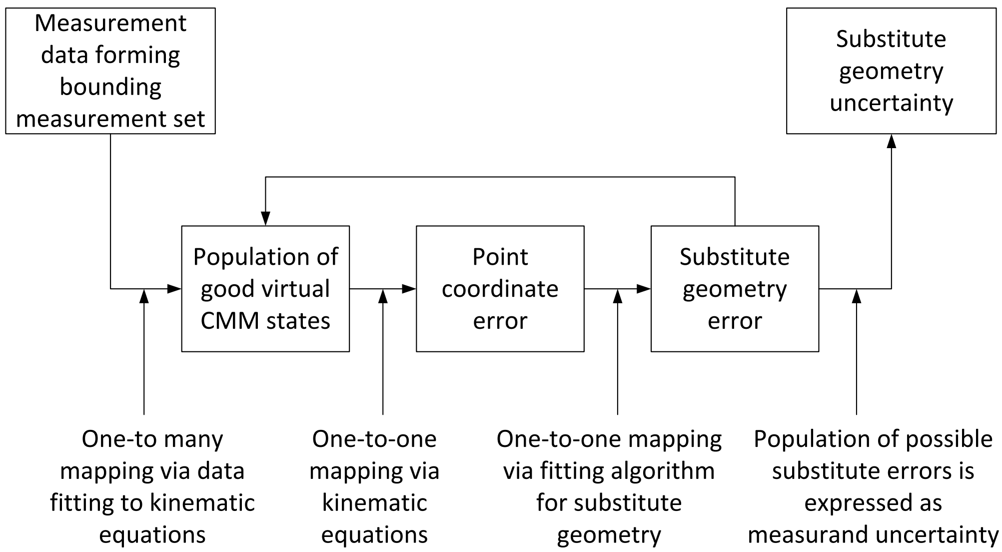


Figure 2-8 Propagation of errors using simulation by constraints.

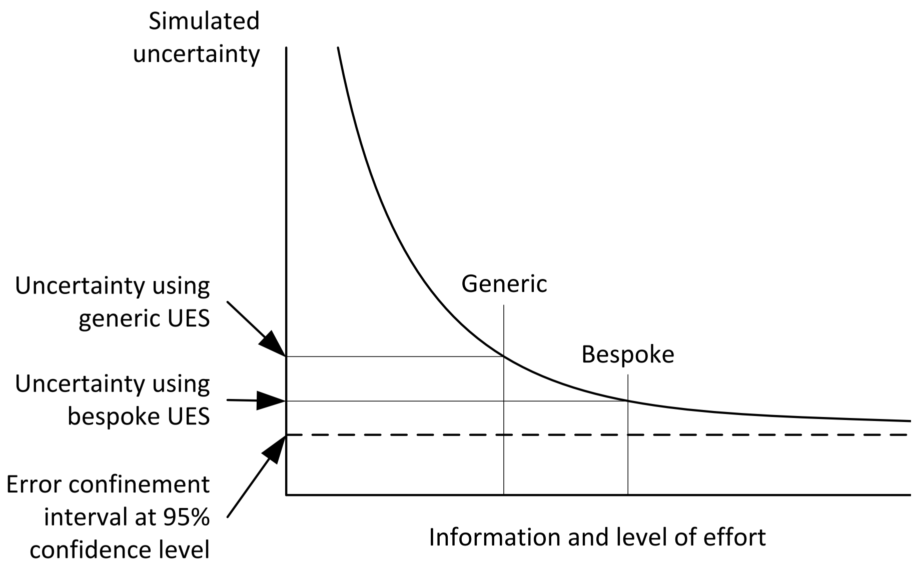


Figure 2-9 Continuum of uncertainty predictions and related effort.

- Measurement history and expert judgement

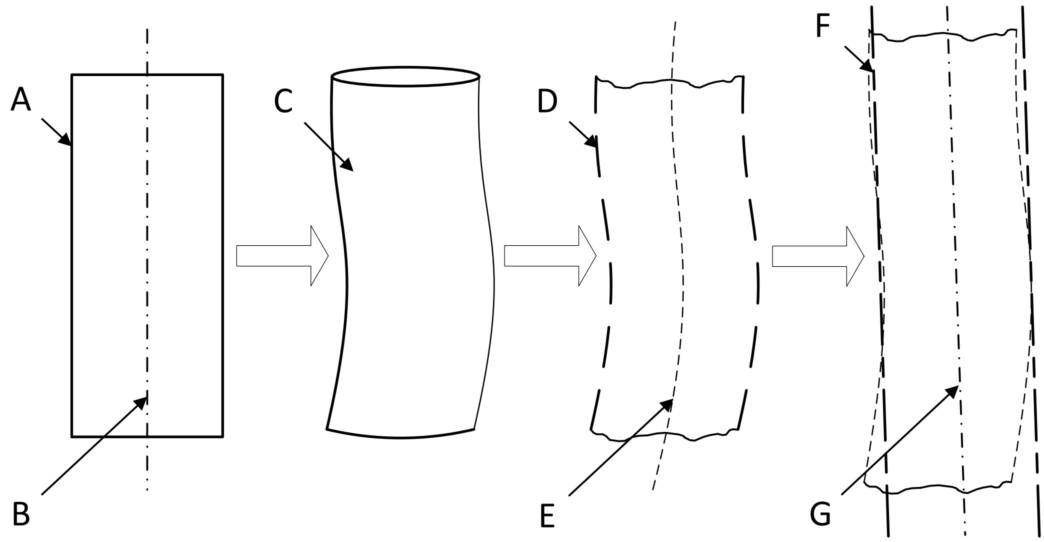
  In addition to sensitivity analysis, comparative approaches, and UES, there are two further options that are alluded to in ISO 15530-1 (2013) – these are measurement history, and expert judgement. There is no guidance within the standards as to how such methods could be validated or put into operation. However, such methods might have an important place within the digital environment where historical records and expert opinion could be systematically captured and used. Moreover, future revisions of the GUM are expected to extend the use of the Bayesian approach (Bich et al., 2012), lending support to the idea of using multiple uncertainty evaluation techniques, so long as they improve the current state of knowledge.

2.5 Frameworks that link specification and verification

What conceptual frameworks exist to link design and measurement?

Traditionally, product specification and product verification were regarded as distinct activities. Such thinking could be justified through the 'time-honoured' principle of process independence, whereby the designer should only specify requirements, not the method of verification (Srinivasan, 2003). Nonetheless, it is clear that there are links between the two activities, and in recognition of this fact ISO/TC 213 was formed in 1996 in order to harmonize standardisation efforts (Srinivasan, 2003). The standards that fall under the responsibility of ISO/TC 213 now provide a comprehensive conceptual framework of how design and measurement could be linked, even if many of the supporting standards are still in their infancy or yet to be written (Nielsen, 2013).

ISO 14660-1 (1999) is a useful standard with which to begin because it designates terms to the different states in which features may exist when a component traverses from specification through to manufacturing and verification. Figure 2-10 shows an example of the different types of feature on a cylinder as it goes on this journey.



Key:

A Nominal integral feature
B Nominal derived feature
C Real feature
D Extracted integral feature
E Extracted derived feature
F Associated integral feature
G Associated derived feature

Figure 2-10 Interrelationship of geometrical feature definitions (BS 8888, 2013).

When the cylinder is specified it has an 'ideal' form, and its features are described as 'nominal'. When the cylinder is manufactured, the features become 'non-ideal' and are known as 'real'. During verification, further 'non-ideal' features are created by sampling the surface; these are called 'extracted' features. Finally, it may be necessary to create 'associated' features from the extracted features to provide an 'ideal' feature to which the nominal feature can be compared, or to define a datum.

2.5.1 Duality principle

Unless the route from specification to verification is defined in detail, there are a number of opportunities to obtain alternative results for the same measurand. As Nielsen (2006) puts it: 'every time an inspector measures the geometrical properties of a part, he or she has to make some decisions about how to make the measurement due to lack of information in the specification.' An example of this is setting up a datum plane from which subsequent measurements will be referenced. According to the 'minimum rock' requirement in ISO GPS (Henzold, 2006, p. 166), the non-ideal real plane feature must be stabilised so that potential movement in any direction is equalised; it may help to imagine trying to position the base of an uneven cereal packet on a hard kitchen worktop. However, on a CMM, only a selection of points, or scans, can be measured on the plane. Depending on the location of the measurement points and how they are analysed, high points could be missed, consequently altering geometry of both the extracted and associated plane features. Vetturi et al. (2013) provides another example in their study on the orthogonality of drilled holes – introducing the words 'non-measurability' and 'non-verifiability', they recommend designers consider whether a geometric specification can actually be verified using existing technology.

In recognition of this potential for inconsistency, the ISO/TC 213 group introduced a concept that they have termed 'duality'. Duality was first described by Srinivasan in

2001 (Srinivasan, 2003), though it was not until 2011 that duality was formally incorporated into the ISO standards as one of the thirteen 'fundamental principles' of the GPS system (ISO 8015, 2011); prior to this time, duality was only referred to within an 'informative annex' in a draft of ISO 17450-1 (2007). According to duality, the designer is responsible for creating a set of ordered operations that emulate functional requirements. The operations are defined using 'specification operators' that cover partition, extraction, filtration, association, collection, and construction. It is then the responsibility of the metrologist to select 'verification operators' that are the physical implementation of the specification operators. The concept of duality is illustrated in Figure 2-11.

In Srinivasan's explanation of duality (Srinivasan, 2003), he notes that partition (such as describing discrete sets of features on a model), collection (for example, treating a group of holes as a pattern), and construction (implying the generation of edges and vertices where geometric elements meet), are all routine activities that happen naturally during the specification process. There is likely to be more room for ambiguity over extraction, filtration, and association, as was noted in the 'minimum rock' example above. Srinivasan (2003) argues that these activities have traditionally been left to the person responsible for defining the verification strategy – i.e. the metrologist. It is the metrologist who would typically determine which points on the surface will be measured – i.e. extraction. It is also the metrologist who would normally decide on how the measurement data will be filtered whether through mechanical means, such as the diameter of a measuring probe tip, or through software, when choosing to exclude 'outliers'. Finally, the metrologist is likely to be the person who decides how the measurement data will be processed in order to create ideal associated features against the non-ideal extracted features – yet the choice of different fit objectives will often result in different solutions, as discussed in Shakarji (2012).

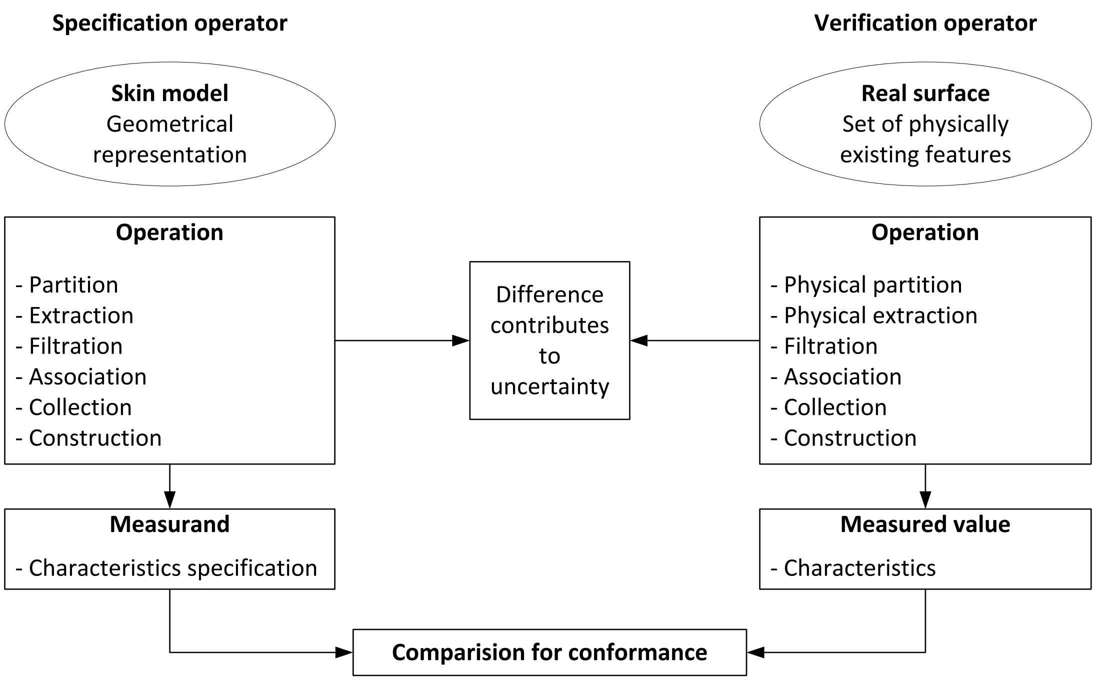


Figure 2-11 Duality (BS 8888, 2011)**.**

Duality recognises that there are choices to be made, and suggests that differences between the specification operators and verification operators contribute to measurement uncertainty (ISO 8015, 2011). Indeed, Nielsen (2013) promotes the idea by arguing that by considering the specification and verification process in its entirety, users are empowered to move away from 'binary' decisions as to whether the verification method is correct or not, towards making decisions on a case-by-case basis – thereby allowing users to evaluate whether a process is fit for purpose.

The duality principle appears to be central to future standardisation efforts within ISO (Nielsen, 2013), and it can be seen that the standards planned for both specification and verification can be mapped according to their location within the duality framework ISO 14638 (2012). For instance, a standard has been recently introduced to permit a range of extraction and association operators to be applied to features of size ISO 14405-1 (2010). As an example, the 'GX/10' modifier in Figure 2-12 specifies that the diameter will be associated using a maximum inscribed algorithm for any portion of the cylindrical portion of length 10 mm. These more detailed specifications are sometimes popularly referred to as PMI 2.0 (Zhao, Brown, et al., 2011, pp. 319–321).

Dantan et al. (2008) provides an example of how duality can be applied to practice. In this source the concept of 'GeoSpelling' is developed, which is an attempt to model the complete tolerancing process throughout the product lifecycle. Building on the specification and verification operators introduced with the duality principle, Geospelling uniquely seeks to build its models from the skin model rather than from nominal models.

There is also research ongoing at the University of Huddersfield, where a system which integrates surface texture specification and verification has been developed based on the operators defined in duality (Qi et al., 2014); similar studies within the group have demonstrated the broader applicability of the approach to geometrical tolerances (Lu, 2012). The surface texture system, 'CatSurf', automates the derivation of specifications given details of the feature, its function, and the manufacturing process. Links between the knowledge domains are encoded using category theory, providing metrologists with information required for verification, such as the direction and length of measurement.

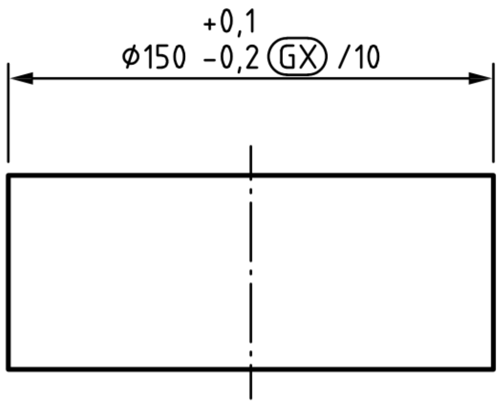


Figure 2-12 Example of PMI 2.0 (ISO 14405-1, 2010).

Finally, there is a short discussion of duality in Henzold (2006, pp. 370–371), which advises that duality is of most use for digital computational metrology where there is currently potential for substantial ambiguity between specification and verification processes. Henzold (2006) suggests that the concept of duality is also likely to be important in high precision environments; this source advices that it is of primary relevance for 'very small tolerances', indicating a figure of twenty micrometres as a potential tolerance value at which one might consider introducing these more sophisticated geometric modelling techniques. Given the ongoing trend to greater use of digital metrology and tighter tolerances, it is surprising that further literature on the topic is scarce.

2.5.2 Total uncertainty model

Related to the duality framework, ISO 17450-2 (2012) develops the idea that measurement uncertainty is actually comprised of method uncertainty and implementation uncertainty. Method uncertainty results when the methods chosen to verify a part do not mirror the way in which it was specified – in other words it is the difference between the actual specification operators that are defined during design and the actual verification operators that are selected by the metrologist (as referred to by the box labelled 'difference contributes to uncertainty' in Figure 2-11). If the verification operators mirror the specification operators precisely, it can be asserted that there is no 'method uncertainty'. On the other hand, implementation uncertainty is concerned with the execution and result of the measurement act itself. It is the uncertainty that arises from the difference between the selected verification operator and a 'perfect' verification operator. It could be argued that implementation uncertainty is what people who have not been introduced to the topic might intuitively equate with measurement uncertainty. However, ISO 17450-2 (2012), defines measurement uncertainty as the sum - in the GUM sense (JCGM 100, 2008) - of method uncertainty and implementation uncertainty.

ISO 17450-2 (2012) goes on to defines two additional sources of uncertainty. Firstly, uncertainty may arise from 'ambiguity of specification'; this could occur when, for example, a specification operator is incomplete. Secondly, uncertainty may arise from 'ambiguity of the description of the function', reflecting the fact that there may not be a clear relation between the specification and the functional requirement for the specified tolerance. Ambiguity of specification is an issue that both the ASME and ISO communities are currently addressing through developing a more comprehensive suite of PMI standards (Srinivasan, 2013); although improving the way that function is described through specification is a considerably more challenging problem (Morse and Srinivasan, 2013). The ISO/TC 213 group go further by promoting the use of uncertainty as a 'currency' (ISO/TC 213, 2012, pp. 1–14) which is perhaps best explained in BS 8888 (2011). It is suggested that manufacturing companies should manage uncertainty across the whole product creation process. The standard gives an example of how it might be foolish to allocate resource to improving inspection capability when ambiguity associated with describing function could be reduced for less cost. Intriguingly, the annex which discussed duality and total uncertainty has been removed from the latest update to BS 8888 (2013).

2.5.3 Quality information framework

A different vision for linking specification and verification is offered by the Dimensional Metrology Standards Consortium. This body has recently released the first version of a set of standards which they have called the *Quality information framework* (QIF) (DMSC, 2013). QIF is described as 'an integrated and holistic set of information models which, if widely adopted, can enable the effective exchange of metrology data throughout the entire manufacturing quality process – from design to planning to execution to analysis' (Zhao, Horst, et al., 2012).

QIF is concerned with data rather than process, employing XML Schema (eXtensible Markup Language) (W3C, 2012) to constrain the format of the data which is exchanged (Zhao, Kramer, et al., 2012). Consequently, QIF does not propose ways in which specification and verification should be linked; rather it provides a shared vocabulary for computer systems.

In researching the data requirements for the entire manufacturing metrology system, the Dimensional Metrology Standard Consortium have arrived at the following classification (Horst et al., 2012):

- Part geometry and its permitted variation;
- Quality management information, such as feature criticality and traceability;
- Measurement resource availability and capability;
- Measurement rules.

The standards group found that much of the data required is only available within individual applications; that is to say, there is a gap in the interfaces. One pertinent example is that a complete semantic representation of PMI has long been absent from open non-proprietary standards. It is anticipated that the PMI gap will be addressed by a new standard ISO/DIS 10303-242, scheduled for release in 2014 (Feeney et al., 2014). However, this would only address one aspect of the information needs for dimensional measurement. In the meantime, flexible yet robust interface formats are needed for exchanging metrology data with engineering design and the rest of the manufacturing system; this is a need which QIF is designed to meet.

2.6 Product lifecycle management

What is the state of art for managing measurement knowledge in PLM?

The research question for the thesis presupposes that PLM could be a useful environment in which to consider the relationship between engineering design and measurement technology. Accordingly, it is informative to consider the background to PLM and how the relevant knowledge could be managed in this context.

2.6.1 Background of PLM

Many attempts have been made to define PLM. Whilst no single definition has emerged (Cheung and Schaefer, 2010), there are common themes. Stark (2005, p. 1) introduces PLM by stating that it is 'the activity of managing a company's products all the way across their lifecycles in the most effective way'. CIMdata (2002) has a similarly wide definition, though uses the words 'product definition data' to more tightly define what is meant by 'product'. Ameri and Dutta (2005) evolve the definition further by arguing that PLM is a 'knowledge management solution which supports processes throughout the product lifecycle within the extended enterprise'. By examining Ameri and Dutta's definition, one can get a sense of the scale for the scope of PLM:

- PLM is a 'knowledge management solution' - it is used to capture, organise, and reuse product data;
- PLM 'supports processes throughout the product lifecycle' - it needs to integrate with all business processes that require knowledge of product definition data from product conception to end of life;
- PLM is used 'within the extended enterprise' - it is not simply an internal tool, but is used when interfacing with suppliers, partners, and customers.

There is no consensus in the literature or within industry as to whether PLM is exclusively an information technology (IT) solution, or whether it should be considered as a business strategy that makes use of IT. For example, Abramovici and Sieg (2002) describe PLM as a 'distributed technological information system'. On the other hand, Ameri and Dutta (2005) and argue that PLM does not have to equate to an IT-only solution – there are aspects about the knowledge of product data which could be appropriate to share through traditional tools such as telephones and notebooks. Nowadays, however, it is commonly expected that IT is a central tranche of a PLM solution (Sääksvuori and Immonen, 2008, pp. 13–21) and the term is widely used by PLM solution providers. For example, Siemens define PLM software as a way of allowing companies 'to manage the entire lifecycle of a product efficiently and cost-effectively, from ideation, design and manufacture, through service and disposal. Computer-aided design, computer-aided manufacturing, computer-aided engineering, product data management and manufacturing process management converge through PLM' (Siemens, 2014). IT-centric PLM solutions are offered by a large number of vendors, however they are now dominated by just three vendors when mechanical engineering design needs to be incorporated: Dassault Systèmes, Siemens PLM, and PTC – although this is increasingly being challenged by Autodesk (Fasoli et al., 2011).

As PLM was beginning to become a recognised term, and in advance of the first international conference on the topic in 2003 (PLM03, 2003), Abramovici and Sieg (2002) published a summary of the results from interviews that were held with seventy-five senior managers from PLM vendors, users and system integrators. Amongst the findings, three interesting results emerged which help to explain how PLM has evolved to where it is today:

- Penetration in industry

  It was found that PLM was taken up most fully by the automotive and aerospace industries, and had a low take-up in the high technology, electronics, and heavy construction industries. It was reasoned that product lifecycle time and product complexity (e.g. number of parts and product variants) are major factors in the impact of PLM in a company. The impact of different drivers is also noted by Cheung and Schaefer (2010), who point out that the functionality required by PLM systems varies significantly across industry types. The finding is significant because it suggests that the automotive and aerospace industries are likely to have had the most experience with PLM and would make useful case studies.

- Integration and interfaces

  Integration with CAD systems was advanced, but in many other areas PLM integration was in an early stage. For example, in computer-aided engineering it was found that data may be exchanged in just one direction, and that analysis tools may not be directly connected. This finding is significant for the relationship between engineering design and measurement technology because, as observed in the historical perspective offered by Voelcker (1998) and current frameworks such as duality and the *Quality information framework*, the disciplines need to be connected through a common information model even whilst 'process independence' is still prized.

- Lifecycle coverage

  PLM implementations were targeted on the product design phase of the product lifecycle. In other words, the focus is on the up-front work in the digital environment. Lifecycle coverage is important to extend the usage of PLM. Indeed, Liu et al. (2005) identified that one of the major trends in PLM will be to attempt to build product and process knowledge earlier in the product lifecycle; this is termed as 'frontloading'. It is also widely observed that a key priority in PLM is to provide feedback, and 'close the gap' between the physical and digital world (e.g. Zheng et al., 2008).

By 2014, just over a decade following this survey, it can be observed that PLM is widely implemented within manufacturing organisations, though (as one might imagine from Siemens' definition), it often represents substantial investment (Rangan et al., 2005).

2.6.2 Integration of measurement knowledge in PLM

Nevertheless, whilst implementation of PLM has widened, there has been relatively little emphasis on the integration of measurement knowledge. This has been highlighted by Maropoulos and Ceglarek (2010), who concluded an extensive review of verification and validation in the product lifecycle, and promote the role PLM could have to play as an integrating environment for the capture, reuse, and maintenance of measurement knowledge.

There are precedents in related disciplines. For example, Jagenberg et al. (2009) give a practical example of how features can be standardized within a PLM environment as a vehicle for capturing manufacturing expertise. As they put it: 'Although almost all engineering companies have internalized the idea of standard parts for reuse, it is often limited to documents and drawings'. This research was conducted at Rolls-Royce plc, where they developed rules with a Siemens PLM system which are automatically applied to features *as they are created*, during design. Toussaint et al. (2010) provide another example of how engineering knowledge, also related to manufacturability, can be reused by implementing predefined expert rules; the system they developed within Dassault Systèmes' PLM software allows design engineers to run manufacturing feasibility studies interactively at various stages of the design process, without the need to develop a standardised hierarchy of features.

2.7 Summary and research gaps

In the previous sections, the literature and state of art for relating engineering design and measurement technology, for the purpose of performing digital measurement planning on CMMs, were reviewed. Beginning from a historical perspective, it was observed that engineering design and measurement technology have co-evolved for hundreds of years. There is no reason to suppose that their future is not also tightly interlinked. Recent trends include digital product definition, digital computational metrology, and the increasing use of PLM systems.

2.7.1 Gap 1: Methods for producing and using PMI across the design-make lifecycle

Traditionally, the allowable geometric deviation of products was defined on drawings using 2D annotations known as 'GD&T'. PMI is the 3D evolution of GD&T. The pace of adoption of PMI has been varied in the mechanical engineering industry, and companies may operate along a continuum of possible approaches for specifying geometric requirements – ranging from a simple 2D drawing which may not even contain GD&T, through to a fully constrained 3D model with PMI. Whilst most authorities advise that PMI should primarily be based on functional requirements, it is also recommended that the needs of manufacturing and inspection be considered. The state of art includes guidelines or automated software tools that check the validity of PMI with respect to measurability. In addition, it is often advised that companies create separate PMI schemes for manufacturing and inspection. However, in practice it was noted that this may rarely happen, and that PMI may become a compromise based on what can be reasonably manufactured and inspected.

> *There is no common approach for producing and using PMI in industry. Trends include the development of standards that incorporate 'duality' – thereby providing the ability to more fully describe geometric requirements. However, such standards are new or emerging, and industry requires guidance on how to make best use of them.*

2.7.2 Gap 2: Prediction of measurement uncertainty for CMMs in an industrial setting

When verifying the geometric requirements specified by engineering design, measurement technology is employed. In this context, measurement uncertainty is a central concept that needs to be understood - both to support conformance decision rules, and to ensure traceability. The standards point out that although measurement uncertainty is of critical importance, the level of effort devoted to calculating uncertainty should be appropriate to business need. Even so, it is challenging to develop uncertainty statements for CMMs because uncertainty is specific to a measurement task and CMMs are capable of performing a large variety of tasks. It is now commonly accepted by National Measurement Institutes and academia that simulation is the only pragmatic way to estimate uncertainty, yet the technique is hardly used within industry.

The standards allude to making use of measurement history and expert judgement; however, there is also little evidence of such approaches being systematically applied in industry.

> *In order to plan for a traceable and consistent verification process, and to provide the data needed to manage uncertainty across the lifecycle, a method is required to predict measurement uncertainty. For CMMs, measurement uncertainty is challenging to estimate and specific to each task. UES is state of art, though hardly employed outside of national calibration laboratories. Research is required to determine the suitability of UES for industry.*

2.7.3 Gap 3: Selection of good practice when developing measurement plans for CMMs

With the ambition of better relating design standards and verification standards, ISO have introduced the principle of duality and the concept of total uncertainty. Duality allows designers to fully define geometry in terms of ‘operators’ that can be mirrored in verification. The difference between specification and verification operators is method uncertainty, where method uncertainty is a part of measurement uncertainty within the total uncertainty model. It is suggested that if method uncertainty could be quantified, one would have a measure of how close the specification and verification processes mirror each other. There is very little literature on duality or the concept of total uncertainty, which is surprising given the trend towards digital models and methods. The Dimensional Metrology Standard Consortium have also been active in taking a holistic approach to metrology, having begun work on a set of information models known as the *Quality information framework*. The consortium has recognised that there is a gap in the ability for disparate systems to exchange metrology data such as uncertainty and measurement rules.

> *With particular reference to CMMs, information regarding good practice is disparate. Industry is in need of a method for choosing between alternate methods for verifying similar features.*

2.7.4 Gap 4: Framework for PLM-integrated dimensional measurement

Finally, the state of art in PLM as a means to manage the relationship between engineering design and verification was reviewed. It was found to be laggard in comparison with other manufacturing processes.

> *Integration of dimensional measurement processes with PLM is in its infancy and there are a growing number of software products targeted at this space. A framework is required against which such solutions can be evaluated.*

Chapter 3 Research design

3.1 Introduction

At the start of this chapter, the aim and sub-questions for the research are presented in the light of the research gaps that were found in Chapter 2. Next, the research methodology to be employed is introduced, along with the reasons for its selection, and its limitations. Finally, research objectives are developed that are compatible with the selected methodology in order to answer the sub-questions and meet the research aim.

3.2 Research aim

The processes used to take a component from detailed design to full production are shown on the left hand side of Figure 3-1; the right hand side lists the validation systems that are enacted. Iteration and feedback is plentiful, though not shown.

As discussed in Chapter 1, in the current system it may often be only once a CMM task has been executed that a lack of capability (or an 'unmeasurable') is identified. This research aims to reduce the incidence of unmeasurables by forming a stronger relationship between measurement processes and design. This will be achieved by developing integrated measurement standards that are cognisant of design requirements and measurement capability. The ambition is indicated by the scroll labelled 'PLM-integrated measurement' in Figure 3-1. In order to investigate this topic, and in view of the research gaps identified in Chapter 2, four sub-questions are developed as follows:

1. What is meant by PLM-integrated dimensional measurement?

   This sub-question is a response to the finding from the literature review that there is no comprehensive theoretical framework available against which PLM-integrated dimensional measurement solutions can be evaluated.

2. How can measurement capability be modelled for use in PLM?

   Uncertainty evaluating software (UES) was found to be a key enabler for modelling measurement capability. However, UES is little used in industry, and no instances were found where UES has been integrated with PLM.

3. What comprises a commodity-specific measurement standard for CMMs?

   Although CMMs have been available for over fifty years, metrologists still debate the best measurement strategies, such as how many points to place on a hole. Thus the question arises as to what is necessary for a standard to be fit for purpose? What should it comprise?

4. How should measurement standards be deployed within PLM to maximise value for Rolls-Royce plc?

   There is no common industry-wide approach for producing and using PMI. Measurement standards could provide that common link. Thus, this question is aimed at determining a practical approach for Rolls-Royce plc to implement measurement standards in PLM.

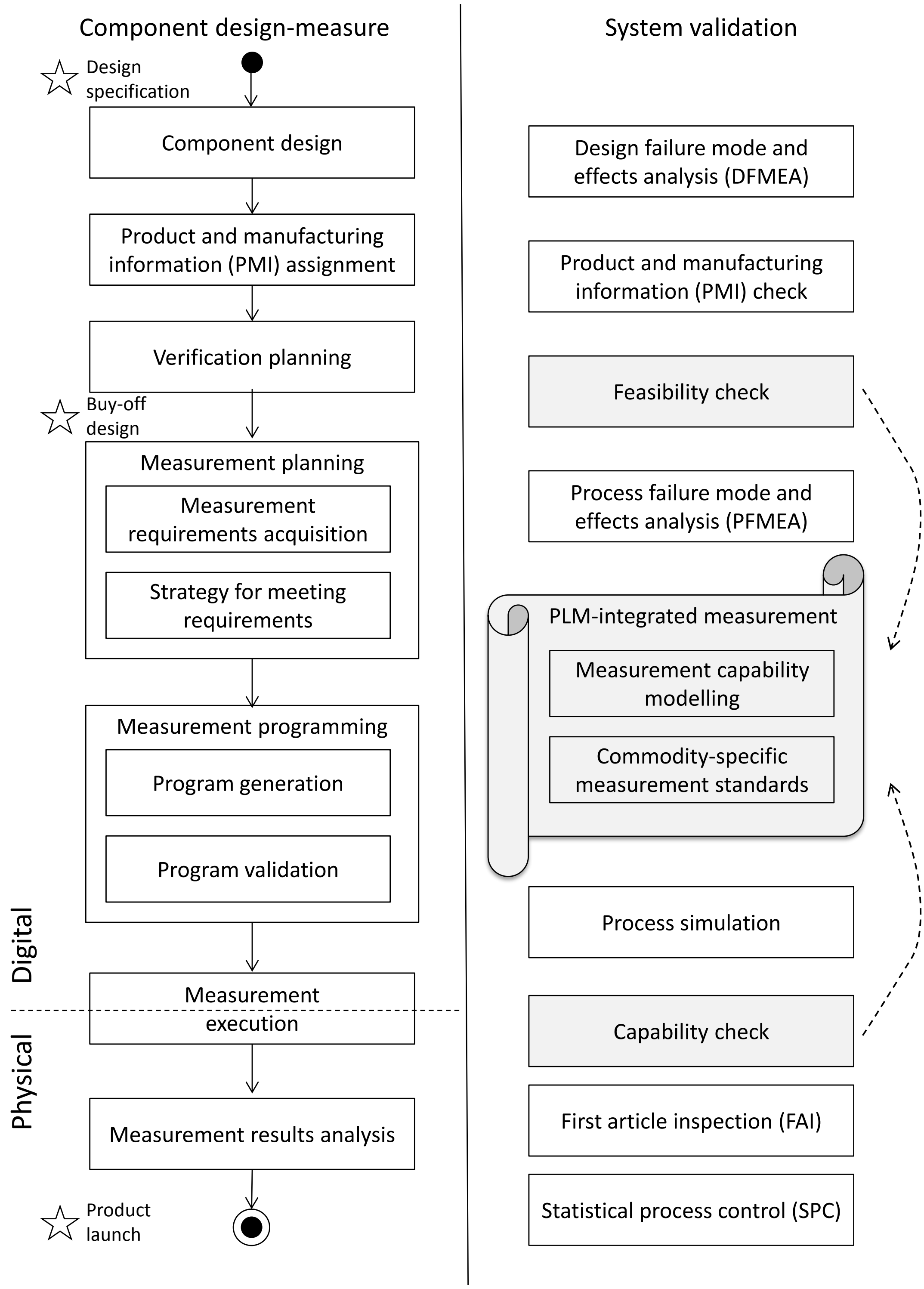


Figure 3-1 Research aim: To strengthen links between measurement and design.

3.3 Research design considerations

The research has been conducted within the framework of the Engineering Doctorate (EngD) in Systems. An EngD is often thought of as a 'PhD in industry'. However, this definition hides many of the differentiators. An alternative definition is that it aims to solve industrial problems with academic rigour. In other words, the requirement for academic rigour is as strong as it would be for a traditional doctor of philosophy (PhD) qualification, though there is the additional requirement for the research to attempt to make an impact on an industrial problem. This implies that an EngD has both an academic and business purpose.

Figure 3-2 illustrates the expectation that the EngD will use academic theory to inform business practice, whilst there is a second purpose of creating theory based on its practical application.

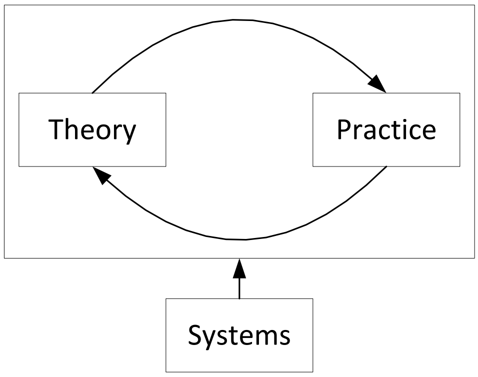


Figure 3-2 Dual purpose nature of the EngD.

Although the EngD has been used as a vehicle for postgraduate research for over twenty years, the 'systems EngD' in which this research is positioned is relatively new, so there is no clear tradition for the philosophical and methodological basis under which this type of research should be conducted. The situation can be likened to that of research in systems engineering which can also be considered to be young, and in which research is often conducted by practitioners; in this field Brown (2009) stresses the importance of the following:

- Research context - understanding requirements, aims, and other contextual issues;
- Research principles - identifying the theory on which the research design is based;
- Research methodology - considering alternative design options;
- Research validity - ensuring a rigorous approach.

All of these aspects – context, principles, methodology, and validity - are considered in the subsections that follow.

3.3.1 Research context

Much of the background to the research, including stakeholder requirements, relevant literature and state of art, and the research aim, has been discussed in the previous chapters and sections. Additionally, it has been noted that the research is being conducted within the umbrella of a 'systems EngD'; accordingly it is expected that systems approaches will be applied to bridge theory and practice, as illustrated in Figure 3-2. The link between research design and systems will be discussed in Section 3.4.

3.3.2 Research principles

What can be said to exist? What is valid knowledge? How do the researcher's values influence the research? What language should be used to describe the research?

These are fundamental questions which guide and inform the research process. As Brown (2009) observes, in some disciplines there are clear precedents, and new researchers may find it necessary to follow these precedents in order for their research to gain acceptance. However, in the field of systems, no clear precedent exists and it is important to consider these issues.

The questions regarding existence and knowledge fall into the realms of the philosophies of ontology and epistemology respectively.

The assumptions made around values can be labelled as axiological, and assumptions about language can be referred to as rhetorical (Collis and Hussey, 2009, pp. 59–60).

- Ontology

  Ontology is the 'study of being as such' (Øhrstrøm et al., 2005) and refers to thinking about the nature of reality. Bryman and Bell (2003) consider ontology from two extreme stances: objectivism and constructionism, sometimes known as research paradigms. The objective stance (which may also be referred to as positivism) supposes that 'social phenomena and the categories that we use in everyday discourse have an existence that is independent or separate from actors' (p. 19); whilst the constructionist view (sometimes referred to as phenomenology) is that 'the researcher always presents a specific version of reality, rather than one that can be regarded as definitive' (p. 20).

  A practical manifestation of the phenomenologist viewpoint is in the field of ontological coaching, as developed by Fernando Flores in the 1980s (Reilly, 1997). Flores argues that ontology shapes the way people behave, and that most of the way they feel about ontology is created by the assessments of others – in other words, it is these assessments that help build an individual's reality.

  Whether a positivist or phenomenologist stance is taken, ontological thinking has implications on many aspects of the research design including what should be studied, how it should be approached, and how results should be used and presented.

- Epistemology

  Epistemology is concerned with thinking about the nature of knowledge. As with ontology, there are major divisions of thought along positivistic and phenomenological lines. The pure positivist position is that a single universal truth exists, and therefore research effort should be directed at increasing this single set of knowledge.

  One way of looking at this is that there is an intersection between truths and beliefs in which all knowledge must lie, but only a certain proportion of this knowledge has been identified and validated. This idea can be simplified by representing 'truths' as 'scientific evidence' (Perla and Parry, 2011), as illustrated in Figure 3-3.

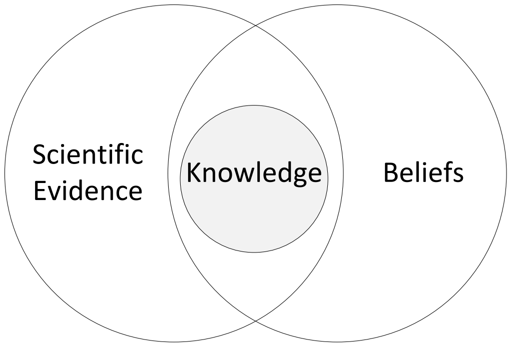


Figure 3-3 Epistemology: A positivistic viewpoint (Perla and Parry, 2011).

In phenomenology, context is considered important because the researcher is an integral part of what is being observed. From a phenomenologist standpoint, Figure 3-3 could only make sense for a particular situation – truths and beliefs are not considered to be static, and therefore knowledge depends on the setting.

- Axiological and rhetorical assumption

  Axiological assumption refers to the role of values and their influence of the research (Collis and Hussey, 2009, pp. 59–60). Related to this, the rhetorical assumption refers to the use of language in the research; for example, whether to write in the first or third person in publications. It is normally expected that the rhetorical assumption made will complement the research paradigm.

3.3.3 Research methodology

The Saunders et al. (2007) onion model (adapted in Figure 3-4) can be used to identify options for research methodology, by considering research paradigms, approaches, strategies, time horizons, data collection, and data analysis methods. Thus it can be observed that there are a wide range of alternatives available to the researcher.

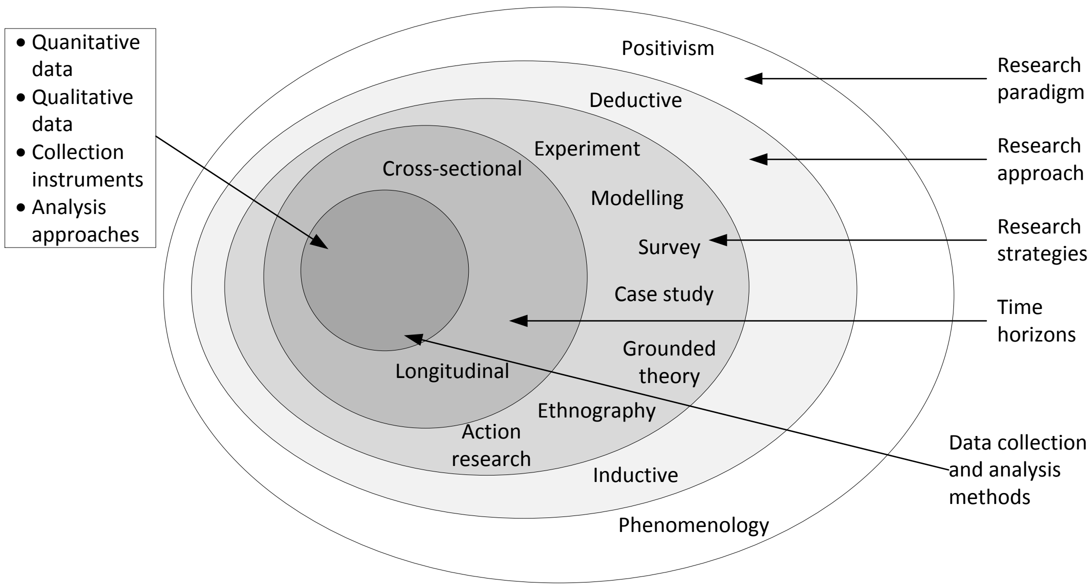


Figure 3-4 Research onion (Saunders et al., 2007).

One might choose inductive approaches, in which one attempts to build theory that is rooted in observational data; alternatively one could select deductive approaches, in which one identifies or develops theory from existing literature, and then attempts to validate it through testing which usually results in creating new data.

Within these broad categories of approach, there are various strategies that can be employed. Some of these strategies are more associated with the deductive approach (such as experiment or modelling); others may be more typically carried out through a more inductive approach (such as grounded theory, ethnography, or action research). A strategy may not necessarily be used exclusively within a particular approach – for example, a survey or case study could be used in either a deductive or inductive mode depending on its design.

Finally, Figure 3-4 is helpful in identifying the need to consider time horizons, data collection, and data analysis methods. All of this needs to be matched up with practical considerations. For example, an EngD is a four year programme, which limits the length of any longitudinal studies that could be carried out.

3.3.4 Research validity

Bryman and Bell (2003, pp. 33–35) regard validity as one of the most important indicators for rigorous research: 'Validity is concerned with the integrity of the conclusions that are generated from a piece of research'. This source suggests that there are four criteria by which validity can be assessed, which are listed below.

- Internal validity

  In essence, internal validity is concerned with whether the research findings are accurate and comprehensive, particularly with respect to any causal relationships that are uncovered. For example, an experimental study would have low internal validity if important correlations are missed between variables that are thought to be independent. For this EngD, where CMM planning is affected by a multitude of factors (for instance, ISO 14253-2, 2011, pp. 10–14, identifies over one hundred variables affecting measurement uncertainty), there is undoubtedly a high risk in this area.

- Measurement validity

  Sometimes known as 'construct validity', measurement validity relates to whether the metric chosen to study a phenomenon is representative of it. This could be an important consideration for this EngD research when considering emerging measures such as 'method uncertainty', whose definition may not be universally well understood.

- Ecological validity

  Findings may be internally valid and use appropriate measures, but become invalid in a 'real' situation. This would indicate low ecological validity. An example of this could arise when research is conducted in a contrived environment that does not legitimately represent the setting in which research would be of use. Again, this is a risk for this EngD study where measurements that are performed in a metrology laboratory may ignore important factors that occur within an industrial environment. This speaks to the value of the research

- External validity

  Finally, it is important to consider how far the findings can be generalised beyond the research context in which it was carried out. For example, although the scope of this EngD is limited to CMMs, external validity would be increased if the research were to be designed in such a way that findings could be generalised for other measurement technologies.

Validity would therefore appear to be a useful measure by which to evaluate the research design. In some cases, it may be necessary to trade one type of validity against another. For example, internal validity is most likely to be achieved in a controlled laboratory environment; however, if one is to rely on laboratory testing alone, ecological validity might be low.

3.4 Rationale for selected research design

3.4.1 Pragmatism

Whilst it is convenient to contrast positivist and phenomenologist paradigms as described in Section 3.3.2, there is actually a continuum of positions between the two extremes. For example, Morgan and Smircich (1980) envisage a range of possible ontological assumptions on reality, as shown in Figure 3-5.

Reality as a concrete structure	Reality as a concrete process	Reality as a contextual field of information	Reality as a realm of symbolic discourse	Reality as a social construction	Reality as a projection of human imagination

Positivist ⟷ Phenomenologist

Figure 3-5 Continuum of ontological assumptions (Morgan and Smircich, 1980)**.**

The research topic under investigation is in the position of trying to link two areas which arguably come from different philosophical standpoints:

- Dimensional metrology – in which an underlying positivist paradigm is typically assumed (Sydenham, 2003);
- Engineering design - in which research philosophy is more frequently debated. For example, at the time of Sydenham's writing, an entire edition of the journal *Design Studies* was devoted to the then emerging topic of 'philosophy of design' (Galle, 2002).

Additionally, due to the fact that the research is being carried out within the organisation being studied, there are significant social and organisational aspects to the research which are expected to be quite specific to Rolls-Royce plc.

For these reasons, it is the author's view that it is necessary to mix positivist and phenomenologist paradigms, making choices case-by-case depending on the particular research objective at hand. This sometimes comes under the name of 'pragmatism'. Indeed, Midgley (2003) argues that it is wise to use multiple approaches - even when using the pure scientific method, objectivity can be lost due to an observer's interpretation. However, the author believes that the degree to which the paradigms are mixed should be limited since there is a danger of adversely affecting the validity of the results. An emerging approach for selecting research strategies and associated paradigms is to make use of a problem solving framework.

3.4.2 Problem solving framework

Intervention using systems thinking has been found to be effective for making robust improvements in the kind of operational context in which the EngD is positioned (Mingers and White, 2009). However, the choice over what research strategy to employ and its methodological context is not easy to defend; the tools of systems are more typically associated with practitioners than with researchers (Huang, 2010), and previous research in the field has tended to shy away from the kind of pluralism associated with systems thinking (Sheffield, 2009). Indeed, there appears to be a gap in the literature as to how systems thinking can be linked with research strategies to bring rigour (Hindle and Franco, 2008; Yearworth et al., 2011). In response, Yearworth et al. (2013) recently introduced the idea of using a problem solving framework for selecting a research design. The concept is borne out of the experience of teaching ninety-six doctoral students in the Systems EngD programme at Bristol University. Within this framework, research is viewed as comprising four phases, similar to the Plan-Do-Check-Adjust stages of the Deming cycle (Yearworth et al., 2013): Exploring; designing (planning for action); implementing (taking action); monitoring/learning.

It is recognised that research questions can arise at any of these stages and have a dynamic flavour. Indeed, the final set of questions listed for this EngD in Section 3.2 evolved only after several iterations of this problem solving cycle. The research strategies can then be selected in accordance with their suitability for answering the research question at hand, as illustrated in Figure 3-6.

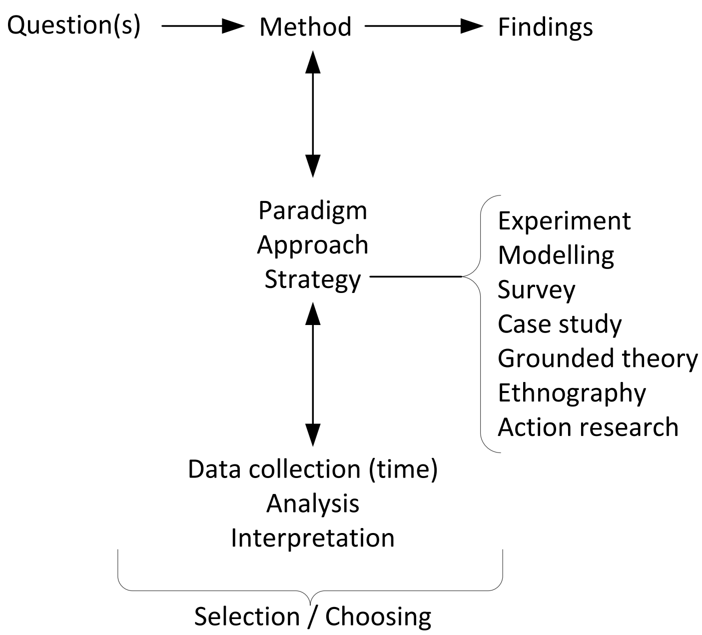


Figure 3-6 Research method as a process (Yearworth et al., 2013)**.**

According to the principles of systems thinking, the choices over which methods are appropriate for answering a question are influenced by the type of problem under study and the purpose of the research or intervention (Elliott and Deasley, 2007, pp. 18–19; Reynolds and Holwell, 2010, pp. 17–18).

3.4.3 Problem characterisation

Most systems have multiple stakeholders whose purposes may not align (Jackson, 2006). Purpose is therefore inextricably linked with the choice of which stakeholders to include (Ulrich, 2003). As Midgley (2003) puts it, ‘the cut-off point for analysis will make some things visible and others invisible’.

The misalignment of purpose between different stakeholders is a key source of complexity within this EngD research. Some of the issues that create complexity in this project have been highlighted by Conklin (2005) as he describes the tension between ‘what is needed’ and ‘what can be done’ (Figure 3-7). The tension is such that roles tend to become polarised into one of the two camps, creating further conflicts.

Conklin goes on to provide a list of characteristics for problems of a complex nature, terming such problems as ‘wicked’:

- ‘You don’t understand a problem until you have a solution’;
- ‘Wicked problems have no stopping rule’;
- ‘Solutions to wicked problems are not right or wrong’;
- ‘Every wicked problem is essentially unique and novel’;
- ‘Every solution to a wicked problem is a one-shot operation’;
- ‘Wicked problems have no given alternative solutions’.

From this checklist, many of the issues faced in this research are of a wicked nature, but it seems that there is some hope to tame the problem. If an inclusive process can be established to link engineering design and measurement technology, the solution may not necessarily be a ‘one-shot operation’; similarly by taking a holistic view of the process, it may be possible to replicate a similar solution in other situations - thus the problem is not necessarily ‘unique and novel’.

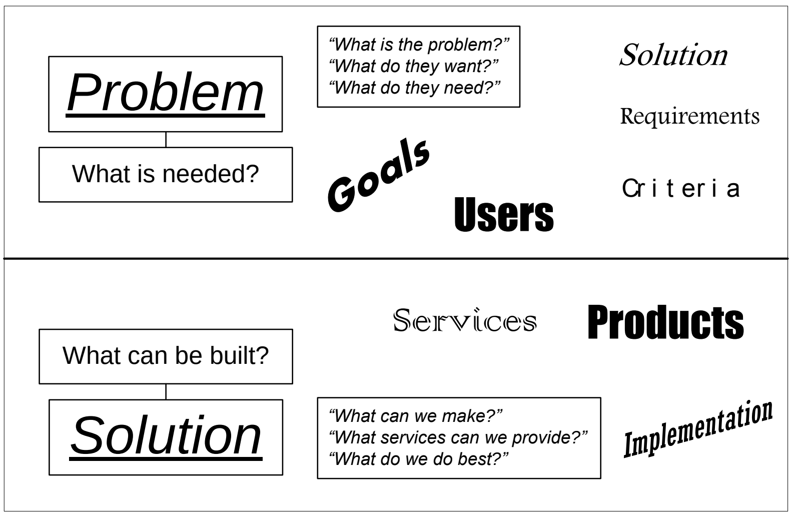


Figure 3-7 Two parts of the world of design (Conklin, 2005).

However, there are aspects to all of the research sub-questions that are inherently wicked. For example, there is unlikely to be a single 'right' answer to the first sub-question: 'what is meant by PLM-integrated dimensional measurement?' PLM-integration might look different to different stakeholders.

In addition to considering whose purposes to include, Oshry (1995, pp. 14–59) identifies two other considerations that have an impact on the system boundary - referring to these as 'blindness' along the dimensions of space and time. Each dimension brings with it implications for purpose. For example, an intervention that improves a situation today for a given stakeholder might not be looked at so favourably by the same stakeholder when reviewed over a longer time period. In order to tackle the right purposes, it is therefore necessary to make good decisions over all types of boundary – people, space, and time. Flood (1999, pp. 129–141) argues that this is best achieved by identifying the relevant boundaries and acting locally to enable 'learning within the unknowable'.

Figure 3-8 is a schematic showing the themes that were reviewed in Chapter 2, placing them according to their relative importance in answering the research questions and the researcher's perception of their ability to influence them at the start of the EngD – that is, how 'local' they are. For example, product specification and verification are highly important, but it is unlikely that they can be changed in the timescale of the project. On the other hand, UES is specialist software and Rolls-Royce plc could be influential in its development.

The implication for the research design is that the methods chosen should facilitate process development in an industrial setting, providing further justification for a pluralistic approach.

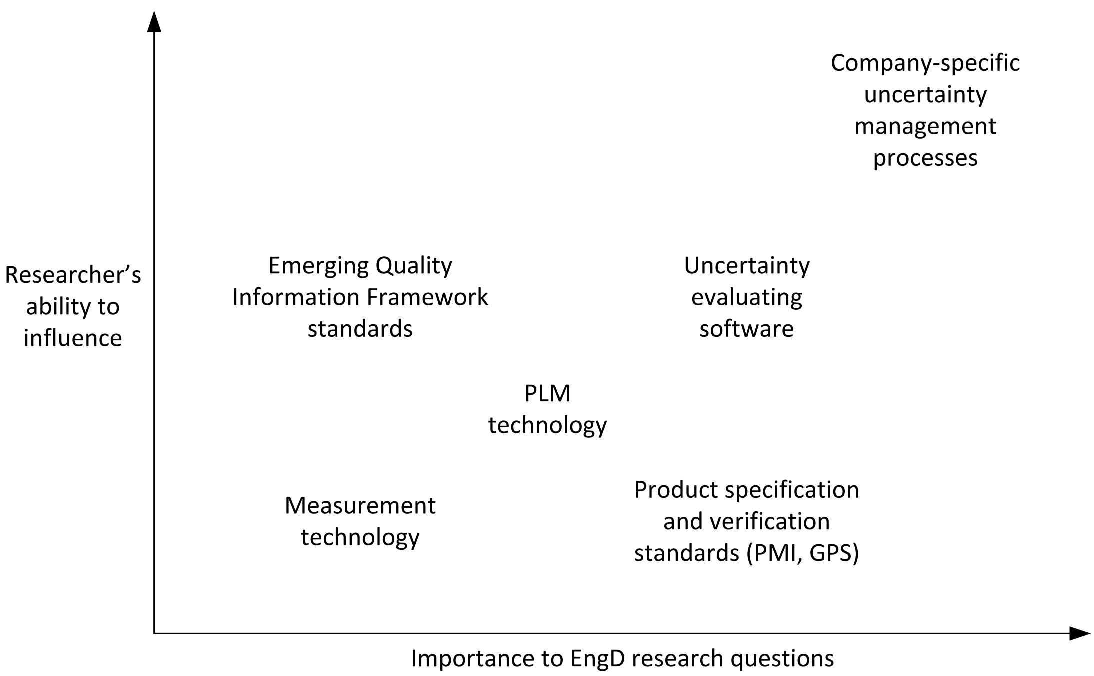


Figure 3-8 Assessment of potential research impact.

3.4.4 Selected research design

The selected research design employs a variety of strategies, as summarised in Table 3-1.

Table 3-1 Research question/method selection matrix.

	Paradigm		Strategy						
	Positivism	Phenomen-ology	Experiment	Modelling	Survey	Case study	Grounded theory	Ethnography	Action research
What is meant by PLM-integrated dimensional measurement?	✓	(✓)	✓	✓	✓	✓			
How can measurement capability be modelled for use in PLM?	✓		✓			✓			
What comprises a commodity-specific measurement standard for CMMs?	✓	(✓)	✓	✓		✓			
How should measurement standards be deployed within PLM to maximise value for Rolls-Royce plc?	✓	(✓)		✓	✓	✓			

Key: ✓ primary selection
(✓) secondary selection

In general, preference was given to the positivistic paradigm, and therefore deductive approaches. This decision was made in order to accord with tradition within applied engineering research. However, there were occasions when the validity of the research and effectiveness of interventions could be improved by employing strategies that are more typically associated with the phenomenological paradigm, permitting more inductive approaches. The methods selected to address each research question are summarised below:

1. What is meant by PLM-integrated dimensional measurement?

   A model was developed following a review of the literature and interviews with stakeholders. An experimental case study was implemented which had the twin purposes of validating the model, and testing a number of systems solutions. Finally, the results were presented in a workshop setting in order to elicit feedback from experts.

2. How can measurement capability be modelled for use in PLM?

   Four studies were designed around the theme of measurement capability. They were designed to challenge boundaries and therefore targeted different parts of the overall problem space within Rolls-Royce plc. The studies could be regarded as ‘action’ cases. Action case is a hybrid research method that can be considered as a combination of action research and case study, in which the researcher is part of the case (Braa and Vidgen, 1999). For example, Gibbons (2012) demonstrated the usefulness of action case as an overarching framework for his EngD in systems.

3. What comprises a commodity-specific measurement standard for CMMs?

   In order to explore the meaning of a commodity-specific measurement standard for CMMs, the model that was developed for the first research sub-question was extended, and additional tests were designed. Laboratory experiments were carried out in order to verify theory.

4. How should measurement standards be deployed within PLM to maximise value for Rolls-Royce plc?

   Finally, in order to validate the previous activities and identify deployment priorities for integrating measurement standards with PLM, further modelling, requirements gathering (through a survey), and case studies were employed in an industrial setting.

3.5 Summary and research objectives

In this chapter, the aim of the research was presented; to strengthen the relationship between measurement processes and design through the development of integrated measurement standards for CMMs.

In order to meet this aim, four research sub-questions were developed that move incrementally from the development of a theoretical framework through to validation in a production environment. Research design options were then introduced, contrasting the positivistic and phenomenological research paradigms.

For this EngD, it was argued that a mixed methods approach is appropriate, with the methods being selected within a cyclical problem-solving framework. The problem that is being addressed can be characterised as complex and there are multiple stakeholders whose purposes do not necessarily accord. In order to develop a research design that is rigorous, exhibits high validity, and provides an opportunity to make a significant industrial impact, the research has been kept local where possible.

Finally, Table 3-2 shows how the research sub-questions can be linked on a one-to-one basis with research objectives; each objective is addressed in a single chapter.

Table 3-2 Research objectives.

Chapter	Research sub-question	Research objective
2	Not applicable. The purpose of this chapter was to identify research gaps as a means to identify critical questions.	To review the literature and state of art in scope of the stakeholder requirements.
4	What is meant by PLM-integrated dimensional measurement?	To develop and test a research framework for relating dimensional metrology processes within the product life cycle.

Chapter	Research sub-question	Research objective
5	How can measurement capability be modelled for use in PLM?	To develop procedures for modelling the measurement capability of CMMs.
6	What comprises a commodity-specific measurement standard for CMMs?	To create a system for developing commodity-specific measurement standards for CMMs.
7	How should measurement standards be deployed within PLM to maximise value for Rolls-Royce plc?	To determine the priorities for improved integration of measurement standards with PLM at Rolls-Royce plc.

Chapter 4 Research domain: PLM-integrated dimensional measurement

4.1 Introduction

Having reviewed relevant literature and state of art in Chapter 2, the second objective of the EngD is to develop and test a research framework for relating dimensional metrology processes within the product lifecycle. Specifically, a framework will be defined that shall be termed 'PLM-integrated dimensional measurement' (PiDM), and solutions will be tested against the framework as a means of cross-validation.

4.2 Problem definition

In this section, the boundary for PiDM is identified, together with the sources of complexity that it attempts to cover. These are important issues in systems research, as discussed in Chapter 3.

4.2.1 Boundary choices

PLM is a vast topic. Possible categorisations for PLM research include:

- Functional perspective - the processes developed in PLM will vary according to the business drivers for a particular domain (Rangan et al., 2005);
- Phase of life - the product lifecycle can be divided into beginning (up to realization), middle (in service), and end of life (disposal or reuse) (Jun et al., 2007);
- Industry type - PLM solutions are most mature in high value discrete manufacturing industries, such as automotive and aerospace (Abramovici and Sieg, 2002).

Due to the nature of the research, it is most relevant to take a high value manufacturing perspective, with the aim of identifying the key elements required to embed quality in the product through the use of dimensional measurement. In order to make the scope manageable, there is a focus on the tail of the 'beginning of life', when geometry is already at a detailed level of definition, though before measurement data can be gathered about how geometry changes when a product is being used; this scoping choice is illustrated in Figure 4-1. The aerospace industry is a useful scenario, since PLM is considered to be advanced in this sector and dimensional measurement can be particularly challenging (Beale, 2012).

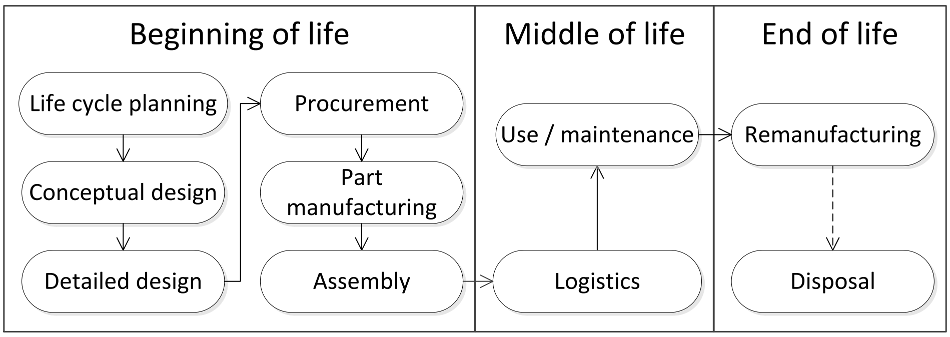


Figure 4-1 Phase of life (Jun et al., 2007)**.**

4.2.2 Sources of complexity

As identified in Chapter 2, there is growing focus on the importance of geometry as the primary and authoritative source of information (Lubell et al., 2012). When geometry is represented in 3D models, with semantic links to the complete set of data that is required to define manufacturing processes, this is known as model-based definition.

If one is to rely on models against which manufacturing methods are associated, those models must be of exceptionally high fidelity (Frechette, 2011). Indeed, Frechette (2011) observed that there are three main technical challenges: model quality and validation; consistent interpretation by applications; and long term archiving, which is a particular problem for aerospace, where lifecycles may be decades long. There are management challenges too, which are highlighted by Marion et al. (2012). By increasing effort in the development of models early in the product lifecycle, designs may appear to be more complete than they actually are, and this can also lead to 'endless tinkering' at inappropriate stages.

Within the model-based definition environment, it is clear that dimensional measurement has a special role to play in providing the feedback needed to improve models. If measurement models could be integrated with design models, it may even become possible for measurement to quantify how 'complete' they are. However, measurement also comes with its own challenges due to its integral place in manufacturing, both in terms of aligning capability, and in its role for decision making.

The difficulty of aligning capability was articulated over thirty years ago by Taniguchi (1983), who extrapolated probable future machining accuracies. The extrapolation has proved to be a useful guide – for example, in the 1980s, accuracy to one micron could only be achieved through a precision machining process, but now this is possible through normal machining in a well-controlled environment. Taniguchi also listed the then available measuring instruments for each level of accuracy, which made the point that there is continual pressure for dimensional measurement techniques to improve over time. The challenge for manufacturers is to ensure that their measuring systems are capable of quantifying size and shape to a level of accuracy and repeatability that is commensurate with the manufacturing process, whilst not over specifying (Orchard, 2011a). This is also confounded by new materials, such as composites, and innovative technologies, such as additive manufacture, which will require new measuring systems to be developed.

Measurement data is used to make decisions. In manufacturing, decisions are made as to whether to pass or reject a part. Additionally, data is used to keep track of processes, and measurement is singled out within the six sigma define-measure-analyze-improve-control improvement methodology (ISO 13053-1, 2011). In order to make better decisions, the level of uncertainty associated with measurement data needs to be quantified. In some circumstances, this may be enforced through regulation. For example, ISO 14253-1 (2013) states that measurement uncertainty should be used in conformance decisions.

In summary, PLM solutions are being built on increasingly comprehensive models. These models are based on 3D geometry. As products progress through their lifecycle, the models should be associated with all the data needed to define the manufacturing process, of which measurement is a part. Challenges include ensuring the model is valid and that data is used consistently and appropriately. Additionally, manufacturing and measurement techniques change over time. For industries such as aerospace, where products may have lifecycles of several decades, there must be a means of managing changes in the method of manufacture. Finally, in recognition of measurement's role in providing data for decision-making, a complete solution for integrating measurement with PLM should consider measurement uncertainty.

4.3 Stakeholder needs analysis

In this section, the location of dimensional measurement activities within the design-make system is explored with respect to stakeholders within Rolls-Royce plc, in order to answer the question:

> *Which dimensional measurement activities and interactions are important to a high value manufacturer?*

One major attempt to define the full set of activities required for dimensional measurement was reported in Evans et al. (2001). The activities were grouped into four types of systems: CAD; programming; execution; and reporting/analysis. Evans et al. (2001) found that there was a lack of standardisation of interfaces both between and within these systems – for example, the interface for planning data within inspection programming was considered to be immature. This systems-based workflow was later refined and documented by Zhao, Xu, et al. (2011) as a multi-layered IDEF-0 model; IDEF-0 is a widely used function modelling language (NIST, 1993).

4.3.1 Identification of valuable activities

Semi-structured interviews, each of 1.5 hour duration, were held with five key stakeholders within the measurement community at Rolls-Royce plc. The questions were targeted at eliciting evidence-based views on which activities are important for performance. A holistic framework suggested by Blockley and Godfrey (2000, pp. 29–56) was used, in which each of the four key processes of product definition, measurement planning, measurement execution, and analysis/reporting (Zhao, Xu, et al., 2011) were examined on the lines of their effectiveness in supporting subprocesses in the domains of business, customer, integration, operation, delivery, and regulation.

The interviews were recorded, and data analysed, in order to build up a picture of how the processes relate to each other using a technique known as hierarchical process modelling (Davis et al., 2010). The resulting model can be explained as a way of arranging processes to find out how and why processes are performed. With reference to Figure 4-2 one looks down the hierarchy to answer questions like 'how is X achieved?' Alternatively, by looking up, one finds answers to questions like 'why is X performed?' For example, the question 'how is the process of verifying products for conformance achieved', can be answered by looking down the hierarchy and finding three processes 'executing measurement processes', 'defining measurement processes', and 'making conformance decisions'.

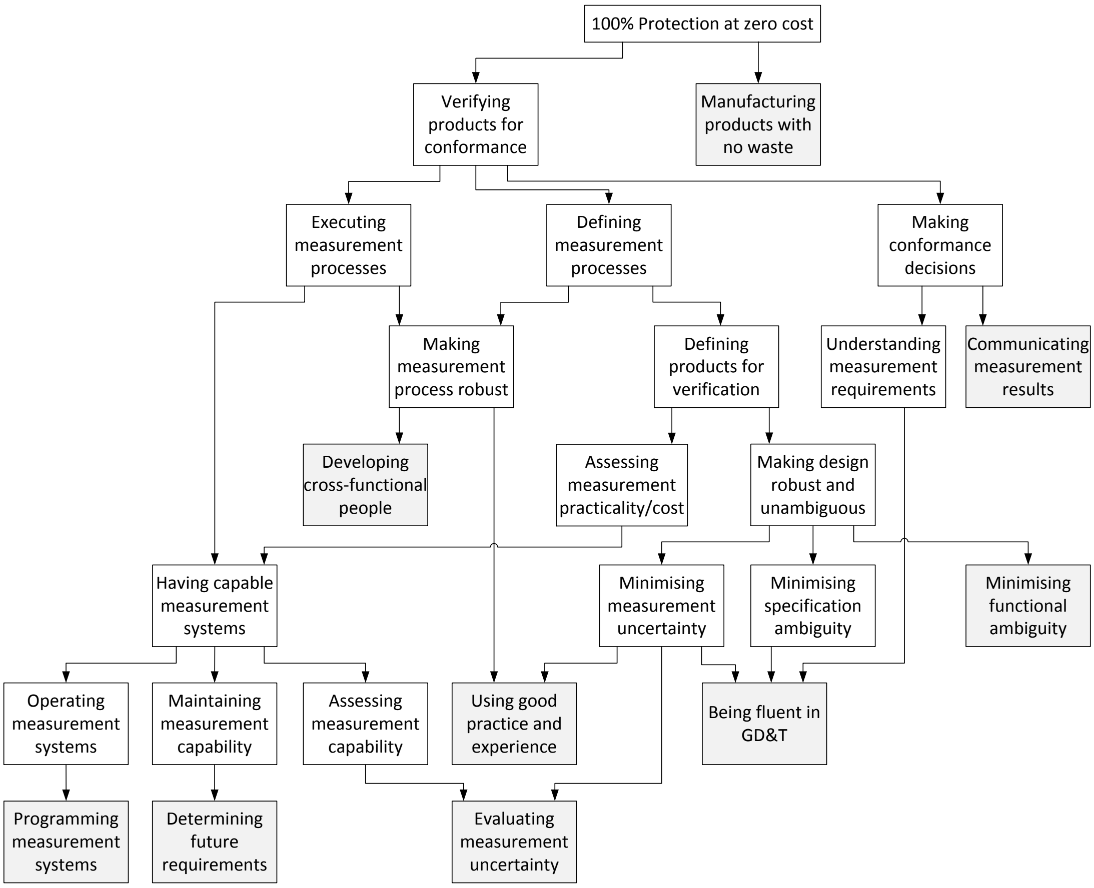


Figure 4-2 Performance view of the dimensional metrology system.

Similarly, if one were to ask the question, 'why is there a process for making conformance decisions', one finds that this helps with 'verifying products for conformance'.

The analysis is clearly subjective. The model is a snapshot of how the author viewed the hierarchy having analysed data from the interviews; it therefore has the potential to be quite remote from the mental models held by the interviewees. The model is also limited by the fact that only one half of the tree was developed; it was considered that for the purpose of this investigation, the processes involved in 'manufacturing products with no waste' were similar enough to those for 'verifying products for conformance'. For these reasons, the model could never be considered 'right'. However, this model has been tested in a variety of ways. Firstly, it was presented to a general audience to solicit comment. The model was then refined in discussions with interested parties. Finally, it was reviewed with key stakeholders. To this end, it has proved to be a useful learning tool and a way of coming to a shared view on which processes to focus in order to improve the overall performance in dimensional measurement.

The key finding is that the activities at the bottom of the hierarchy (shaded boxes) are essential for the success of the measuring system. On this account, the model has proved its usefulness by highlighting priorities for the business and why they are important; these priorities are highlighted in Figure 4-3.

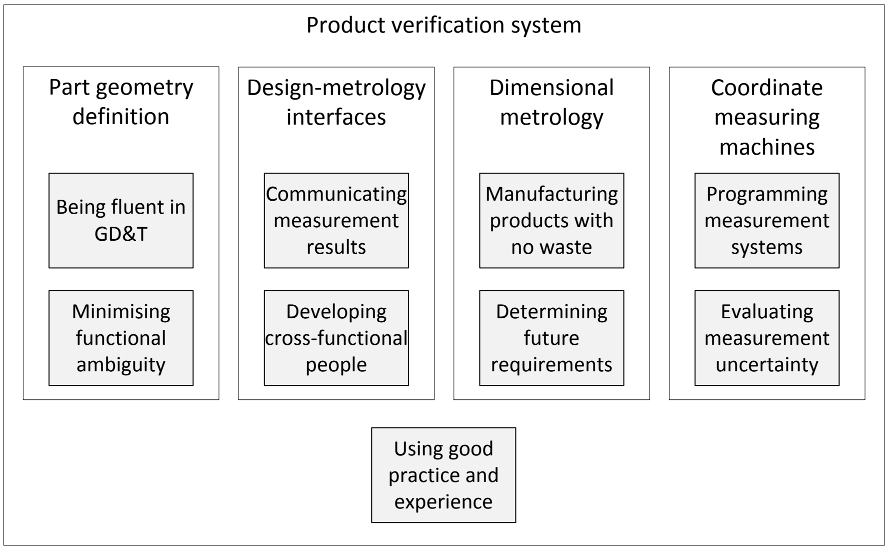


Figure 4-3 Business priorities in dimensional measurement.

4.3.2 Identification of process interactions

The interviewees were also asked to mark up the interactions, as they currently see it, between the main processes of product definition, measurement planning, measurement execution, and analysis/reporting, as identified through the research in Evans et al. (2001) and Zhao, Xu, et al. (2011). These starting processes are shown as shaded boxes in Figure 4-4.

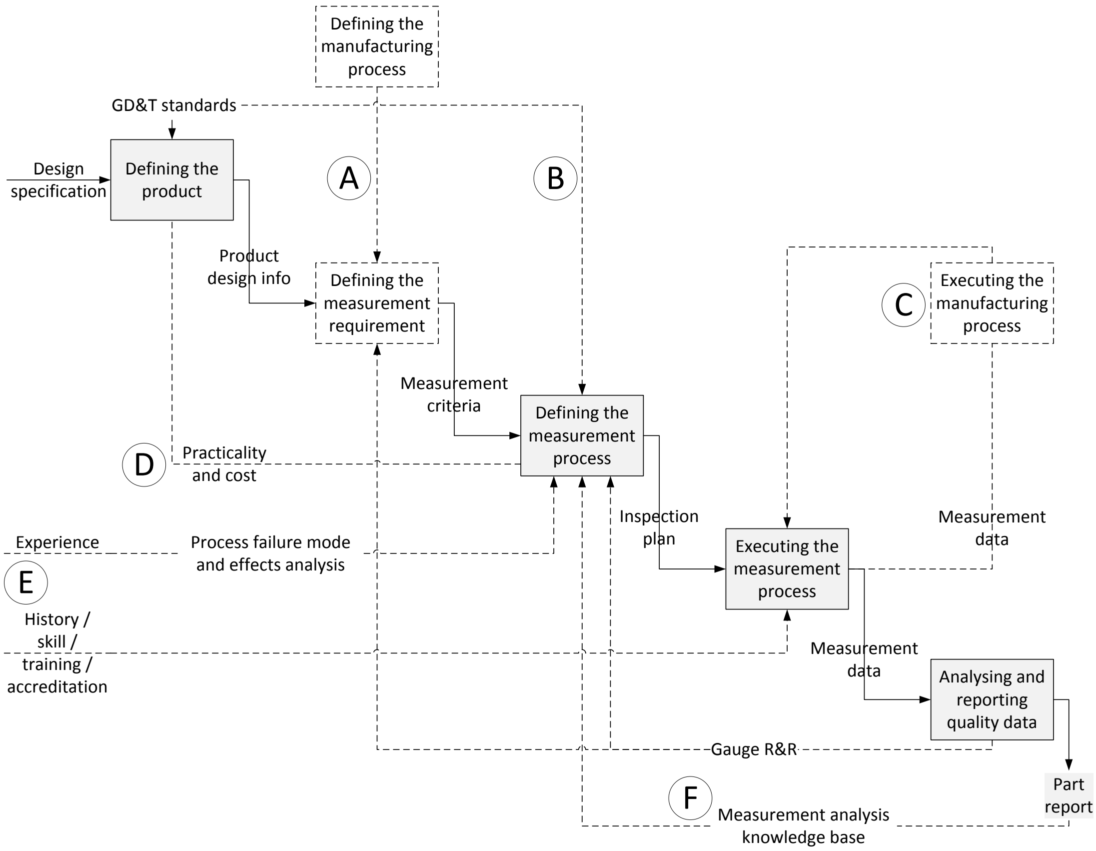


Figure 4-4 Workflow view of the dimensional metrology system.

Each interviewee gave a unique picture of how they saw the measurement process operating. Nonetheless, some common themes emerged. The dotted boxes shown represent instances where one or more interviewees felt compelled to draw a new process; the dotted lines shown represent places where two or more interviewees agreed on a relationship between processes.

The interviews identified four main issues that appear to require attention:

- Efficient use of GD&T to communicate requirements [B];
- Integral nature of measurement in manufacturing [A, C];
- Formal identification of measurement objectives [A];
- Prevalence of feedback [C, D, F].

Given the small (though expert) sample size, it is difficult to draw rigorous conclusions. However, it was interesting that all interviewees commented on the impact that manufacturing processes have on measurement, and that it was important enough to warrant separating out as a process of its own. Similarly, the interviewees all felt a need to document feedback loops to reflect the interrelated nature of processes, including an apparent desire to stress the importance of GD&T. Whilst the baseline process model might suppose that GD&T flows down to the planning stage as an output from product definition, several interviewees felt it important enough to emphasise this link. Finally, there is a significant human element that needs to be accounted for at all stages. The words 'judgement' and 'experience' were used on a number of occasions to describe the process flow.

4.4 Framework for PLM-integrated dimensional measurement

In this section, a framework for relating dimensional metrology processes within the product lifecycle is developed. The framework aims to cover the complexities reviewed in Section 4.2 whilst focussing on the needs of stakeholders identified in Section 4.3.

Since the subject of the framework is high value manufacturing, the telecommunications industry may seem like an eccentric place to look for literature. Yet it is here that one can find a good exemplar of a business process framework, in the shape of the *enhanced Telecom Operations Map*™ (eTOM) (Kelly, 2003). Telecom operators 'make' products, such as mobile phone or internet services, through a mixture of physical activities (e.g. installing new cables) and software activities (e.g. activating email accounts). eTOM attempts to describe all the activities that are needed by Telecom operators to run their business, and locate these activities on a layered map. For example, to complete an order for a new mobile phone service, a service fulfillment process will be enacted. The fulfillment process will interact with functions relating to customer relationship management, service management, resource management, and supplier management. At each stage, the required processes are named, and solution vendors can indicate which of these eTOM processes they cover. eTOM thus provides a standard means of communication; business process professionals within telecoms need to be conversant in eTOM in much the same way as manufacturing engineers should be familiar with the language of GD&T. The lesson from eTOM is that it is valid and useful to generically map organizational capabilities through a simple, prescriptive, matrix of processes. Accordingly, an eTOM-inspired framework will be developed to describe the necessary processes in PLM-integrated dimensional measurement. The framework will take the form of a simple grid showing PLM functions against a dimensional measurement workflow. In accord with the scope of the EngD, there will be a focus on CMMs since dimensional measurement is most mature in this area, and CMMs are a dominant measurement instrument within the aerospace domain for which the framework is targeted.

4.4.1 Dimensional measurement workflow

The issues identified in the stakeholder interviews relating to GD&T, measurement in manufacturing, measurement objectives, feedback, and making use of best practices and experience, are made explicit in the workflow shown in Figure 4-5.

The workflow begins with component design, in which CAD is used to create a 3D model of nominal geometry. The permitted variation of shape and size is then defined by assigning GD&T callouts (generalised to PMI on the diagram) to features on the model. Verification and process planning is carried out to determine the strategy for verifying GD&T requirements and the sequence of manufacture. In some cases, it may be found that verification can take place with minimal dimensional measurement – for example, a feature might be verified through the control of process inputs during manufacturing. Following the identification of measurement objectives, measurement planning determines the measurement tasks, instruments, probing strategy, and probe path. Programming and execution is carried out to create and run a CMM program. Finally, the results are analysed, and trends may be reviewed during component variation analysis. By arranging these steps in a 'V', one can see how measurement enables feedback, answering questions like: Did the execution go to plan? How closely was the specification met? How did reality differ from design?

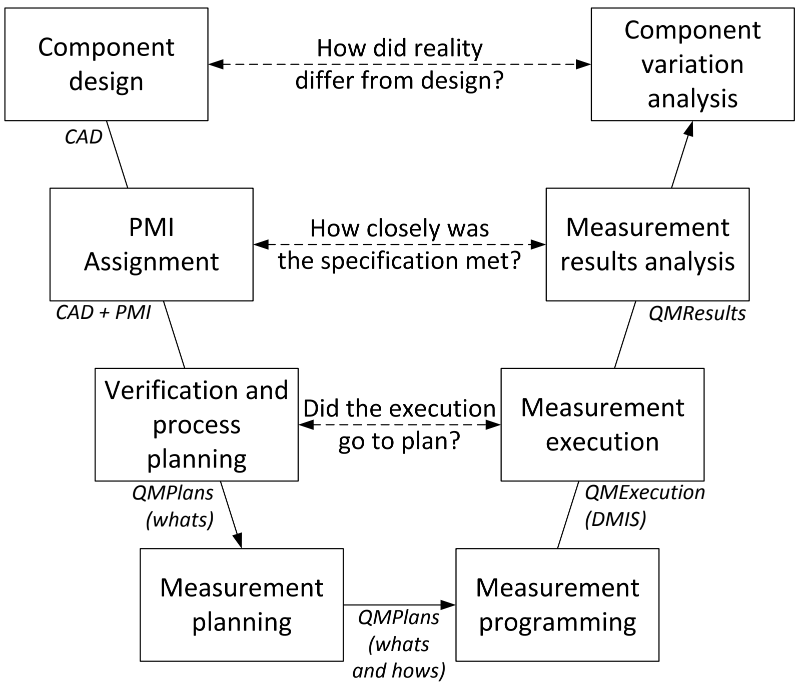


Figure 4-5 PiDM Framework: Dimensional measurement workflow.

Through most of the workflow, the interfaces can be described using the *Quality information framework* (QIF) (DMSC, 2013), which was described in Section 2.5.3. In this first version, the focus for QIF has been on QMPlans, QMResults, and QMExecution - where 'QM' stands for 'quality management'. QMExecution is already implemented through the dimensional measuring interface standard (DMIS) (ISO 22093, 2011). QMPlans can be further distinguished between the 'whats' and 'hows'. The roles of these interfaces are largely self-explanatory when located against the workflow in Figure 4-5 - full details can be found in the standards documentation (DMSC, 2013).

4.4.2 PLM operational context

Campbell et al. (2011) discuss the need for customers to describe the operational context in which a system will be used that is independent of vendor capabilities. Whilst such context will by definition be customer-specific, the framework attempts to cover a superset of functionality that should be evaluated.

PLM was conceived to manage product data, so it seems reasonable to include this as a central element for the PiDM framework. Furthermore, the discussion on sources of complexity in Section 4.2.2 noted that there is a need to:

- Align measurement and manufacturing capability;
- Account for the decision-making role of measurement;
- Use measurement to provide feedback in order to improve models.

These issues will therefore be used to derive the other main aspects, as shown in Table 4-1. The operational context thus shows aspects of PLM that should be considered when navigating the workflow.

Table 4-1 PiDM Framework: PLM operational context.

PLM aspect	Responsibilities
Data management	Capture and organisation of data needed to support the dimensional measurement workflows.
Metrology resource management	Allocation and optimisation of measurement resources, allowing for measurement capability.
Verification and validation	Verification that activities are done right; validation that the right activities are done, and; providing information for decision-making.
Feedback	Communication of change to design, manufacturing, and measurement

4.4.3 Example: More stringent tolerance

Imagine a component is in the early stages of detailed design. In order to support a concurrent engineering methodology, measurement plans and programs have been generated, even though the model has not yet been bought off. Now imagine that a review has taken place and the tightest tolerance on the drawing became tighter.

> *What might one expect from a PLM-integrated dimensional measurement solution?*

One can work through this scenario by following the dimensional measurement workflow considering the PLM functions of data management, metrology resource management, verification and validation, and feedback.

Initial questions may be raised, as shown below and as referenced in Table 4-2:

1. Can the reason for the changed tolerance be recorded? [Q1]
2. Will this have an impact of the feasibility of measuring the feature? [Q2]
3. How will this information be fed back so that the sampling strategy can be reviewed? [Q3]
4. Is the currently selected measurement instrument capable? [Q4]

Table 4-2 Applying PiDM to the example of a more stringent tolerance.

Process step in PiDM workflow	Data management	Metrology resource management	Verification and validation	Feedback
PMI Assignment	[Q1]			
Verification and process planning			[Q2]	[Q3]
Measurement planning		[Q4]		

Even though Table 4-2 only shows three of eight steps described for the dimensional measurement workflow, and none of the interfaces, the framework now prompts additional questions. For example, reflecting on just the PMI assignment step, one might wish to know the cost of the change on the manufacturing process (a verification and validation question), and how this information should be best relayed to design (a feedback question).

It is important to note that the framework was developed without any consideration of the software packages that would be used – in other words, it is vendor neutral. It was reviewed by the stakeholders of the project, and was presented to an international peer-reviewed conference (Saunders, Cai, et al., 2013) for feedback. The framework has proved to be a useful tool for communicating issues and benchmarking solutions. Importantly for this research, it has enabled technology gaps to be systematically identified, as described in the next subsection.

4.5 Cross-validation case study

Having agreed the theoretical framework, a set of test cases was defined to test the system. These are based around a pair of relatively simple artefacts. The artefacts had been designed for a previous EngD project that was undertaken for Rolls-Royce plc, and incorporates features that are common on aerospace components - including scallops, a freeform wave profile, and cylindrical features with deliberate form error (Lobato, 2011, pp. 3/3–36). They will be known as the 'Rolls-Royce multi-feature artefacts', and are pictured in Figure 4-6; there is a 'Block A' and a 'Block B', as indicated by the markings next to the holes and on the central boss.

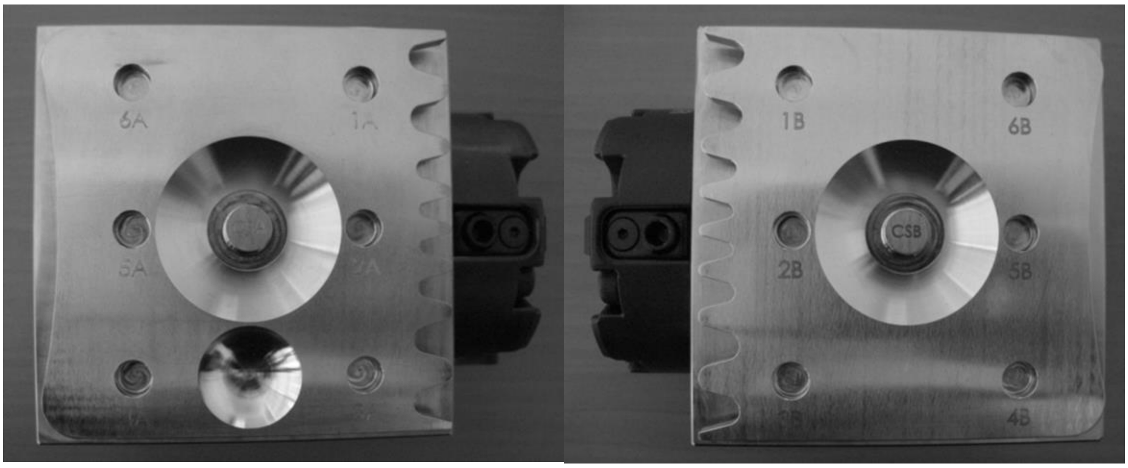


Figure 4-6 Rolls-Royce multi-feature artefacts.

Block A and Block B are nominally a mirror image each other, with the exceptions of a scallop on the top surface of Block A. However, the form error that was deliberately introduced to the holes and boss are different between the two blocks. This is of only minor relevance to validating the PiDM framework, though it is central to process development activities that are reported in Sections 5.5 and Chapter 6. Representative PMI was added to Block A (which includes the scallop), on the understanding that this could be read across to Block B. The PMI was added in consultation with a representative from Siemens who has expertise in this field. The PMI is shown in Figure A-1.

4.5.1 System test methodology

The aim of the test cases was to achieve a good level of coverage of the scenarios that PLM-integrated dimensional measurement would be expected to cover. Accordingly, the following process was followed:

1. A four-by-four matrix of possible changes that could be made to the feature or PMI was formulated. These can be considered as 'categories' of test cases, and are shown in Table 4-3.
2. For each category, instances of test cases were identified and named. There were seven categories for which no test cases could be envisaged, the scenario was considered unlikely, or an equivalent case was already covered in another test category – these are labelled 'N/A' (not applicable). This resulted in fifteen test cases. For example, in the category 'Feature: No change / PMI: Modify' four test cases were created.
3. For each test case, a short description was provided, together with a summary of the task and prerequisites; the prerequisites are conditions that must be met before the test case can be run. For example, in the case of 'moveDatum', it was determined that it would be necessary to have a program that includes the measurement of the holes which act as the old and new datum features. For this test case, it is also required that the part program includes measurement of other callouts that refer to the datum.
4. The four aspects within the PLM operational context were then considered in order to prompt questions as to what one might hope to achieve within PLM-integrated dimensional measurement. An example of the resulting test

case for 'moveDatum' is shown in Table 4-4. The drawing, test cases, and a summary of the questions are provided in Appendix A.

5. Finally, the scope of the test cases was reviewed against the dimensional measurement workflow that was developed for the PiDM framework. In total, seventeen additional test cases were identified to cover other steps in the areas of PMI assignment, measurement planning, measurement programming, measurement execution, and measurement results.

Table 4-3 Test case categories and names.

		PMI No change	Remove	Add	Modify
Feature	No change	N/A *(nothing changed)*	removePMI	addPMI	modifyProfExtent modifyProfTol modifyProfDatMod moveDatum
	Remove	removeHole1	removeHole2 removeHole6 removeBoss	N/A *(unlikely)*	N/A *(covered in remove/remove)*
	Add	addScallop	N/A *(unlikely)*	addBoss	N/A
	Modify	moveHole	N/A *(unlikely)*	N/A *(unlikely)*	changeHoleSizeAll changeHoleSize4

Table 4-4 Test case for 'moveDatum'.

	moveDatum
Category	Feature: No change / PMI: Modify
Description	Move Datum C from a 'good' to 'bad' feature
Prerequisites	Program for part measurement that includes measurement of hole 5A, 2A, and all callouts that refer to Datum C
Task summary	Move Datum C from Hole 5A to 2A
Data	How is the history stored? Can you revert back? How does the software update the feature library? How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? E.g. does it add new identifiers? Will the measurement planning module see the PMI changes made by design? Does the path change?
Resource	Not applicable.
V&V	Do datums have a different sampling strategy? Is this applied to the new hole?
Feedback	Will the software highlight that the newly selected datum is of a lower quality that the previous datum? E.g. can you add process capability information against the feature, or bring in data obtained from previous measurements? Will the software highlight affected PMI?

The generation of test cases was somewhat iterative, as additional tests were conceived during the test period. In total, thirty-two test cases were developed, resulting in fifty-three unique questions. The full set of test cases and questions are provided in Appendix A.

Where possible, questions were consolidated so that they would only need to be answered in the first test case in which they were encountered. Finally, the test cases were peer reviewed to ensure appropriate specification and coverage.

Two testing environments were created using the following software products – essentially representing a Siemens solution, and a Hexagon solution:

- Siemens Teamcenter 9.3, BCT Inspector Suite, NX 8.5.1 CMM, CMM Inspection Execution;
- Hexagon PC-DMIS 2012 MR1, PC-DMIS Planner.

These software products were chosen because Siemens and Hexagon were participants of the project and were willing to offer their solutions and expertise. Ideally, additional software would also have been investigated, though it was felt better to concentrate on those solutions where product knowledge was accessible to the project.

4.5.2 Technology gaps

The test cases were executed in the two solutions, under the guidance of the software vendors. During this process, research opportunities and technology gaps were identified and recorded using a multi-media web-based tool (Sharpcloud, 2014).

From the common gaps which were found, the most significant were as follows:

1. Selection of the measuring system

   Both solutions require the measuring system to be selected by the user, so how can the user know whether the measuring system is capable or appropriate? For example, a PiDM solution could provide recommendations, such as scanning for certain profiles, or it could advise on constraints over tip diameters where access is difficult.

2. Sampling strategy

   Standard rules for point placement, such as BS 7172 (1989) and ISO 14406 (2010), are not available out of the box. Indeed, considerable skill and experience is required to select an appropriate measurement solution. There is scope to make this easier since both solutions permit a multi-level approach to developing sampling strategy (component family / part / feature), yet this would require significant investment on the part of users to configure.

3. Path generation / optimisation

   Paths are generated for features before being connected by transition moves, so this can sometimes result in unnecessarily long moves.

4. Working with PMI

   It can be challenging to work in 3D. For example, it is critical to assign PMI callouts to the correct feature(s) otherwise measurement features will be incorrectly identified.

4.5.3 Physical demonstration

A practical demonstration was also carried out as described in Table 4-5,

Table 4-6, and pictured in Figure 4-7. The CMM systems will be encountered again in Chapter 6 and Chapter 7, and are therefore described as CMM A, CMM B, and CMM C for brevity.

Table 4-5 Overview of PiDM demonstrations.

Demo	Software	I++ Client	I++ Server	CMM
1	PC-DMIS	PC-DMIS I++ Client	PC-DMIS I++ Server	CMM A
2	PC-DMIS	PC-DMIS I++ Client	Renishaw UCC Server	CMM B
3	NX-CMM	Inspection Execution	Renishaw UCC Server	CMM B
4	NX-CMM	Inspection Execution	Renishaw UCC Server	CMM C

Table 4-6 CMM systems at the Manufacturing Technology Centre.

	CMM A	CMM B	CMM C
CMM	Leitz PMM-C	Nikon LK 15.12.10	Nikon LK 30.20.20
Probing system	LSP-X1c	PH10M	Revo
Maximum permissible error	0.6 µm + L/600 µm	1.9 µm + L/375 µm	3.0 µm + L/400
Probe error	~0.2 µm	~0.92 µm	~2.0 µm
Temp. range	20 ^{o}C ± 1 ^{o}C	20 ^{o}C ± 1 ^{o}C	20 ^{o}C ± 1 ^{o}C

Note: CMM B was equipped with a TP200 probe for the demonstration in Chapter 4 and an SP25 for the experiments in Chapter 6; the value for 'Probe error' refers to the SP25.

Figure 4-7 Pictures of demonstration (demo 1, 2/3, and 4 from left to right).

The demonstration led the following generic observations which were discussed with the stakeholders:

1. Troubleshooting

   It was sometimes difficult to determine the source of a problem in this multi-system environment.

2. Feature-specific issues

   The ‘wave’, on the side of the artefact, was found to be hard to measure. There were also some stylus ball collisions that were not found during simulation.

3. Simulation

   Simulation is important to avoid crashes and should not be skipped. However, it cannot be fully relied on and it is necessary to invest effort into understanding its capabilities (e.g. what types of collisions are detected?). Another simple, though easily overlooked point is that the model must accurately represent the part being measured.

4. Efficiency

   The time to author a basic program was around fifteen minutes in both solutions, as opposed to around two hours for an experienced programmer using more conventional methods. Additionally, optimisation is critical for measurement speed – some wide variations were observed, therefore optimisation may be critical for many users. Accordingly, the communication of ‘measurement purpose’ is critical in order to develop the most appropriate strategy for both the initial authoring and subsequent optimisation of a measurement program.

Following the demonstration the stakeholders fed back the following key points:

1. There is a need for collaboration between metrology and PLM vendors;
2. A desire was expressed to keep future research close to commercially available technology, in order to maintain interest of the software vendors;
3. The importance of setting defaults (such as the number and location of measurement points) was stressed by the technology users. It was also noted that defaults would need to be calculated dynamically since they are dependent on the task.

4.6 Summary

This chapter addressed the second objective of the EngD, which is to develop and test and research framework for relating dimensional metrology processes within the product lifecycle. The presented PiDM framework is deliberately theoretical to avoid it becoming unduly influenced by existing solutions prior to testing against real products. Test cases were designed and executed within the framework based on two generic artefacts. The test cases were designed to be broad in scope; they made a foray into all aspects of integrated dimensional measurement, which were categorised as data management, metrology resource management, verification and validation, and feedback.

The framework has proved to be a useful means of identifying technology gaps, and identifying system boundaries for future research. It has also reinforced the findings from the literature and state of art review in Chapter 2. Looking specifically at PLM-based CMM measurement planning, the following additional technology gaps were identified:

1. Sampling strategy determination is not optimised in practice;
2. Measurement uncertainty evaluation could help optimisation, but occurs in isolation of PLM;
3. Measurement results are poorly linked back to measurement planning, contrary to the theoretical ideal of the PiDM workflow.

Chapter 5 Procedures for modelling measurement capability of CMMs

5.1 Introduction

This chapter addresses the third objective of the EngD: To develop procedures for modelling the measurement capability of CMMs. The research is connected to the findings in Chapter 4, where technology gaps were highlighted around employing measurement uncertainty evaluation techniques to optimise sampling strategy for CMMs, and making use of historical measurement results. A series of related studies are presented, which have the common objective of exploring the technology needed to address these gaps within an industrial setting.

5.2 Study 1: Decoupling measurement from process capability

In the first study, an attempt was made to incorporate existing measurement capability data into an industrial PLM environment. The opportunity to conduct the investigation followed on from the exploratory study in a robust multidisciplinary design optimisation environment for turbine blades which was referenced in Chapter 1. This earlier exploratory investigation reinforced the view that benefits would arise from including the measurement objectives explicitly with the robust multidisciplinary design optimisation system which was being developed.

Following discussions with the project team, the global measurement process owner, and the business metrologist from the group, it was agreed to begin by developing a procedure for decoupling measurement uncertainty from process capability indices (which are a blend of manufacturing process variability and measurement uncertainty). It was thought that since capability indices were already being employed in the unit cost model, that this would be a pragmatic first step to account for measurement processes within the design optimisation process.

The part in question was a turbine blade, and the measurement data was taken from a pair of CMMs that are situated in a critical point of the manufacturing process immediately after the main manufacturing datum features are created, though prior to further feature creation. A representation of the type of component (Rolls-Royce, 2011b) and CMM (Mitutoyo, 2014) are pictured in Figure 5-1.

Figure 5-1 Study 1: Part (left) ©Rolls-Royce plc; CMM (right) ©Mitutoyo (UK) Ltd.

5.2.1 Problem definition

Process capability indices, and in particular C_{pk}, have become ubiquitous in manufacturing. As Hare (2007) comments, their popularity may be partly explained as *apparently* simple measures that 'separate good from bad'.

C_{pk} is perhaps easiest understood by first considering its cousin C_p. This index compares the width of the process to the width of the engineering tolerance – typically at six standard deviations:

$$C_{\mathrm{p}} = \frac{\text{Tolerance}}{\text{Process variation at } 6\sigma} = \frac{USL - LSL}{6\sigma} \qquad [5\text{-}1]$$

where

USL = upper specification limit
LSL = lower specification limit
σ = standard deviation derived from the results of a process

One analogy that is sometimes used is that of trying to park a car (which represents the spread of a process at six standard deviations) into a garage (which represents an engineering tolerance). In these terms, C_p can be thought of as the number of car widths that can fit within the garage, as illustrated on the left of Figure 5-2. It is interesting to note that in this example, the car could be parked outside of the garage, and still have a C_p of two. For this reason, C_{pk} was developed, which brings in an evaluation of the centre of the process:

$$C_{\mathrm{pk}} = \min\left(\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right)$$

$$C_{\mathrm{pk}} = \frac{d - |\mu - m|}{3\sigma} \qquad [5\text{-}2]$$

where

μ = mean value of the characteristic produced by a process
d = half-length of specification interval = $(USL - LSL) / 2$
m = midpoint of specification interval = $(USL + LSL) / 2$

The difference between C_p and C_{pk} increases as the mean value produced by a process moves away from the midpoint of the engineering tolerance, as shown pictorially in Figure 5-2. In this example, the width of the car and the garage are unchanged, meaning that C_p equals two in both the left and right example; however C_{pk} is reduced from one to one third when the car is moved two standard deviations to the right. This can be derived from equation [5-2].

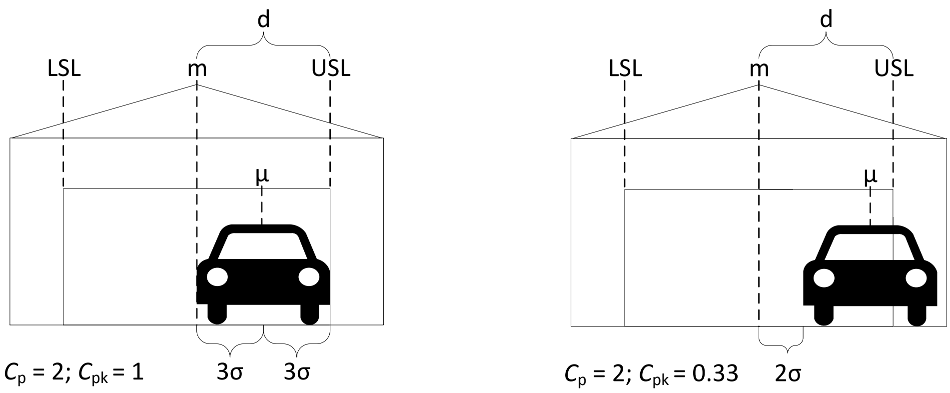


Figure 5-2 Car in garage analogy for C_p (left) and C_{pk} (right).

There are many other process capability indices in existence. However, C_{pk} is widely used in Rolls-Royce plc, and is the index of choice in the PLM system under study, where it is used to derive manufacturing yield. Consequently, it seems to be a useful hook to which one can introduce measurement uncertainty.

Measurement error will always be present in the measurements that are used as a basis for calculating process capability indices. Since measurement is an inherent part of the manufacturing process, it cannot (and perhaps should not) be readily divorced from it when considering overall process capability. However, it is suggested that there is value in understanding how much of the total variation in process is due to measurement to help focus improvement effort, as suggested by Kunzmann et al. (2005). The question to be answered for this study is as follows:

> *Can the variation due to measurement be de-coupled from the observed C_{pk} in the context of this industrial setting?*

5.2.2 Derivation of a true capability index

The literature on the impact of measurement uncertainty on C_{pk} is scarce; however there are a few exceptions. Notably Bordignon and Scagliarini (2002), building on the research of Mittag (1997), have shown that both sampling error and measurement uncertainty can have a significant effect on the observed C_{pk}. They found that sampling error can tend to overestimate C_{pk} when the sample size is small, although the bias is reversed for high sample sizes. This means that for small sample sizes, the overestimating effect from sampling can offset the underestimating effect from measurement variation. However, using the concept of a contamination degree, tau, as shown in equation [5-3], they show that when contamination is high, measurement errors will always lead to a systematic under-evaluation of $C_{pk,}$ no matter what the sample size.

$$\tau = \frac{\sigma_{\text{meas}}}{\sigma_{\text{true}}} \qquad [5\text{-}3]$$

where

σ_{true} = theoretical standard deviation (if no measurement error)
σ_{meas} = standard deviation due to the measuring system

It is suggested that for many processes within Rolls-Royce plc, the contamination degree is indeed high. Additionally, it is likely to remain high so long as one sees improvements in machine tool accuracy, and increasing pressure to minimise spend on the measuring system which is not regarded as adding value to the process. Moreover, a search of company documentation showed that Rolls-Royce plc has acknowledged that measurement uncertainty can have a significant effect on the calculation of process capability, and that this should to be more widely recognised in the business.

For these reasons, it was proposed that it could be useful to develop a function that adjusts the C_{pk} which is observed, to determine an adjusted 'true' value of C_{pk} that excludes variation from the measuring system. This function could be built into the PLM system to provide a value for the yield costs associated with measurement variation. Such a function is derived in equations [5-4], [5-5], [5-6], and [5-7] below.

Assuming measurement variation is independent of process variation and that both are normally distributed:

$$\sigma_{\text{obs}}^2 = \sigma_{\text{true}}^2 + \sigma_{\text{meas}}^2 \quad [5\text{-}4]$$

where

σ_{obs} = observed standard deviation, including measurement error

From equation [5-2], it can be seen that C_{pk} is inversely proportional to σ, thus:

$$\frac{C_{\text{pk,true}}}{C_{\text{pk,obs}}} = \frac{\sigma_{\text{obs}}}{\sigma_{\text{true}}} \quad [5\text{-}5]$$

where

$C_{\text{pk,true}}$ = 'true' process capability index, excluding measurement error
$C_{\text{pk,obs}}$ = observed process capability index, including measurement error

Substituting with equation [5-4]:

$$\frac{C_{\text{pk,true}}}{C_{\text{pk,obs}}} = \sqrt{\frac{(\sigma_{\text{true}}^2 + \sigma_{\text{meas}}^2)}{\sigma_{\text{true}}^2}} \quad [5\text{-}6]$$

$$C_{\text{pk,true}} = C_{\text{pk,obs}} \cdot \sqrt{\frac{(\sigma_{\text{true}}^2 + \sigma_{\text{meas}}^2)}{\sigma_{\text{true}}^2}}$$

$$C_{\text{pk,true}} = C_{\text{pk,obs}} \cdot \sqrt{\frac{\sigma_{\text{true}}^2}{\sigma_{\text{true}}^2} + \frac{\sigma_{\text{meas}}^2}{\sigma_{\text{true}}^2}}$$

Substituting with equation [5-3]:

$$C_{\text{pk,true}} = C_{\text{pk,obs}} \cdot \sqrt{(1 + \tau^2)} \quad [5\text{-}7]$$

In order to calculate a 'true' C_{pk} that is independent of measurement variation, a method for calculating the measurement variation is required. Ideally, one would use data from measurement uncertainty studies, such as those referenced for CMMs in Section 2.4.4. However, it is common to find that the only data readily available relating to measurement uncertainty are gauge repeatability and reproducibility (GRR) studies.

As the name suggests, a GRR study establishes both the repeatability of a measurement process, and its reproducibility. GRR provides a result per measurement feature in the form of 'precision-to-tolerance'; methods for performing GRR are described in AIAG (2010). For example, it may be determined that the spread of the variation from a measurement process at 6σ occupies a quarter of the available tolerance - this would be said to have a '25 % GRR', as described by equation [5-8].

$$GRR = \frac{6\sigma_{\text{meas}}}{Tolerance} \quad [5\text{-}8]$$

By making the assumption that GRR fully represents measurement variation, and by substituting equations [5-8] and [5-3], equation [5-7] can be restated as a function of GRR. Note that this is a simplification and the implications are discussed in Section 5.2.4.

$$C_{\text{pk,true}} = C_{\text{pk,obs}} \cdot \sqrt{\left(1 + \left(\frac{Tolerance \times GRR}{6} \div \sigma_{\text{true}}\right)^2\right)} \quad [5\text{-}9]$$

Substituting with equation [5-4], this can be restated as follows:

$$C_{\text{pk,true}} = C_{\text{pk,obs}} . \sqrt{(1 + \upsilon^2)} \quad [5\text{-}10]$$

where

$$\upsilon = \frac{Tolerance \times GRR}{6.\sqrt{(\sigma_{\text{obs}}^2 - \sigma_{\text{meas}}^2)}} \quad [5\text{-}11]$$

Recalling that σ_{meas} is a function of GRR and the engineering tolerance (as described in equation [5-7]), and given that σ_{obs} must be known to calculate $C_{\text{pk,obs}}$ (as described in equation [5-2]), it follows:

$$C_{\text{pk,true}} = f(C_{\text{pk,obs}},\ GRR,\ Tolerance) \quad [5\text{-}12]$$

5.2.3 Implementation in the PLM system

The following method was implemented in order to decouple measurement uncertainty from C_{pk}:

1. For each standard design feature, the related measurands were identified.

   Twenty-eight design features on the turbine blade were in scope of the study. With only one exception, there is a one-to-many or many-to-many relationship between the design feature and the measurands which are monitored in order to verify that it meets its design specification and manufacturing requirements; accordingly, there are a total of eighty-five measurands.

2. Determine the GRR precision-to-tolerance value for each of the related measurands.

   It was found to be problematic to acquire current GRR values for the measurands due to the CMM's criticality in the production line. For this reason, historical GRR on equivalent features was used where such data was available; this is also common practice when introducing design changes into manufacture. A repeatability test was also performed, with ten repeats, for all the measurands; results from the repeatability test were used where data from historical GRR was not available, or when the repeatability values were found to be higher than those from the historical GRR. However, problems were found with some of the results from the repeatability study; the measurement data had been rounded to an insufficient number of decimal points to provide confidence over the calculated standard deviations. In fact, several features were reported to have zero deviation. In any case, one would expect a repeatability test to account for only a small fraction of the total measurement uncertainty.

3. For each design feature, choose the related measurand with the highest GRR value (i.e. the poorest measurement capability).

   The related measurand with the highest GRR was considered to be the one to watch – this measurand will be referred to as the 'key measurand'; fourteen such measurands were identified.

4. Apply the equations in Section 5.2.2 to assess the impact of GRR on C_{pk}

An example of how the mapping from design features through to the calculation of the associated $C_{\mathrm{pk,true}}$ is shown in Table 5-1.

5. Finally, the existing cost models were adjusted by another group involved in the project, in order to account for the cost of an imperfect measurement process.

Table 5-1 Example calculations of true C_{pk}

Design Feature and Key Measurand		Tol / mm	GRR	$C_{\mathrm{pk,obs}}$	s_{obs}	s_{meas}	υ	$C_{\mathrm{pk,true}}$
F-1	M-1	0.1	0.188	1.17	0.00626	0.00313	0.577	1.35
F-2	M-5	0.3	0.053	1.10	0.00789	0.00263	0.354	1.17
F-3	M-9	0.15	0.102	2.05	0.00372	0.00186	0.577	2.37

Note: GRR is updated when GRR studies are performed;
The sample standard deviation, s, is used in place of the population standard deviation, σ;
$C_{\mathrm{pk,obs}}$ and s_{obs} contain the observed process capability data;
s_{meas}, υ, $C_{\mathrm{pk,true}}$ are calculated as per equations [5-8], [5-11] and [5-10] respectively.

5.2.4 Discussion

The presented method of adjusting the observed process capability using GRR data is appealing for its apparent simplicity. However, it masks a number of difficulties.

1. Sampling error is ignored

   In some cases, a low sample size can underestimate C_{pk}, hence potentially offsetting any adjustment (Bordignon and Scagliarini, 2002). However, when the contamination degree, tau, is high, measurement variability is expected to dominate.

2. Timescales may not match

   There are issues as to the timescales over which C_{pk} and measurement uncertainty is calculated. Uncertainty contributions are typically assessed over a long time period (e.g. temperature fluctuations over one year); however, C_{pk} is often calculated from data that is gathered over a relatively short period of time. For the existing cost models, a few months of data have been used to determine the C_{pk} values; although this was found to be a statistically significant set of data, there could be difficulties in comparing this with measurement system variation which may be calculated over a different period of time.

3. Normality is assumed

   The calculations outlined in the previous section assume that the variation from manufacturing and measurement processes both have normal distributions. Whilst the central limit theorem lends weight to this assumption, it can be questioned. Would one expect a manufacturing process to have a normal distribution when it is frequently adjusted (either manually or automatically)? The assumption of normality for measurement processes, in particular on CMMs, is also doubtful (Baldwin et al., 2010).

4. Poor availability of measurement uncertainty data

   It was found to be problematic to obtain data on measurement uncertainty. For this reason GRR data was used which does not include an analysis of bias and therefore represents only a portion of total uncertainty. Moreover, in this investigation it was found that GRR studies existed only for a limited number of measurands in scope of the study.

5. Measurand selection

   Finally, it happened that the measurement process related to the design features in this case was found to be highly capable in terms of GRR (low precision-to-tolerance values). Thus the value of the intervention was hard to justify.

5.2.5 Study summary

In this study, the researcher set out to introduce a new procedure to quantify the value of a CMM measurement process in terms of its influence on C_{pk}. This was motivated by a desire from the business to consider measurement issues within PLM. Although such thinking exists in the literature, no detailed examples were identified so the exercise was deemed valuable. On attempting to implement the procedure, it was found that measurement uncertainty data was not readily available. The CMMs in question were heavily utilised and the necessary uncertainty studies could not be performed. Consequently, the developed procedure made use of historical GRR and repeatability studies which were found to cover only a subset of measurement uncertainty and are only infrequently reassessed.

An alternative method for assessing uncertainty, and consequently make better choices about which measurands to include in a detailed study, is investigated in subsequent sections.

5.3 Study 2: Virtual measurement systems analysis

One of the findings from the first study was that measurement uncertainty data is challenging to obtain in a manufacturing environment, especially for CMMs. In the second study, the researcher attempted to overcome this difficulty by utilising measurement uncertainty evaluating software (UES), sometimes known as a ‘virtual CMM’ (Section 2.4.4).

The business need for this investigation arose from the fans production facility at Rolls-Royce plc where there was a requirement to demonstrate the capability of the verification process for a new product through a procedure known as measurement systems analysis. This was proving to be problematic because it was estimated that it would take around eighty hours to achieve this through physical studies on the target CMM, yet the machine was not available for this length of time because measurement on the CMM is a bottleneck operation. In addition, there was a lack of resource available to conduct the capability studies. The part in question was an outlet guide vane assembly, and measurement is performed in a shop-floor environment following final machining operations (Figure 5-3).

Figure 5-3 Study 2: Part (top); CMM (bottom).

5.3.1 Problem definition

All the key characteristics on the outlet guide vane are measured on the CMM. The study was targeted on these key characteristics in order to identify the ones which are may require further study, as illustrated in Figure 5-4. Thus, although the part has a high number of features, there are actually only eleven measurands in scope of the study, and these can be further categorised into three functional groups as shown in Table 5-2.

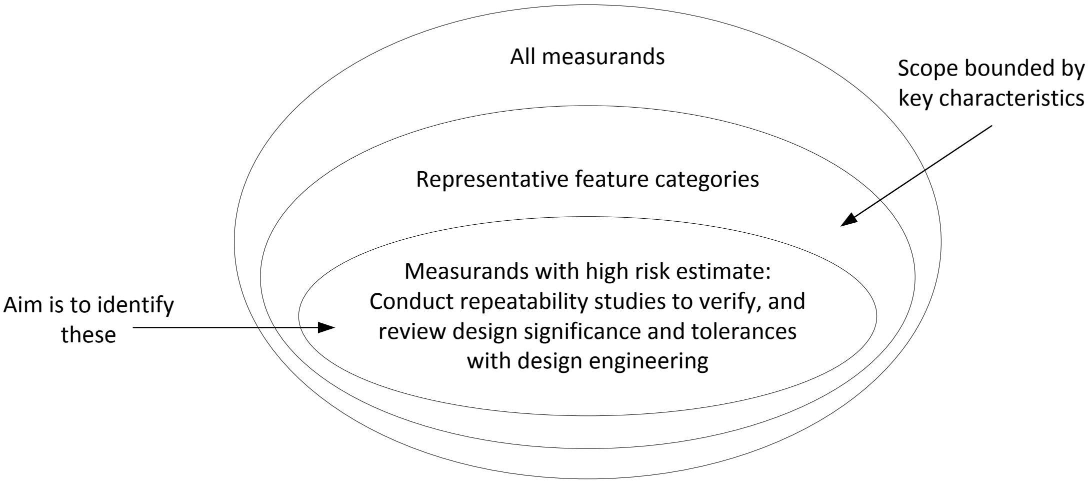


Figure 5-4 Scope of virtual measurement systems analysis.

Table 5-2 Categories of key characteristics.

Group	Measurand	Nominal / mm	Tolerance / mm	Reason for status as a key characteristic
1	Front to rear flange height	101.6	±0.1	The height tolerance must be maintained so that flanges do not distort during assembly and to avoid reducing bolt torque.

Group	Measurand	Nominal / mm	Tolerance / mm	Reason for status as a key characteristic
2	Outer gauge point radius (leading edge) Outer gauge point radius (trailing edge)	1490.9 1473.39	±0.15 ±0.15	The outer dimensions of the part are designed for a transition fit. The end faces must be in contact when assembled in order to take shear and vibration loads from the outlet guide vane assembly.
3	Front bolt hole position Rear bolt hole postion	791 805	±0.25 ±0.25	If the position accuracy is not maintained, costly rework would be necessary during the next stage of assembly.

The CMM is a DEA Lambda 3707 gantry CMM. With a working volume of 4.2 m × 4.2 m × 1.5 m, it was Rolls-Royce plc's largest CMM at the time of carrying out the study and was the only CMM available to perform the measurement. This CMM is approximately 20 years old and is fitted with a Renishaw TP20 probe in a PH10M motorised indexing head.

The outlet guide vane assembly is a low volume part. Measurement system analysis is time consuming and necessary, yet the CMM is seldom available for measurement trials. Additionally, new products may go through a period of relatively frequent change – whenever a change takes place, the measuring system should be re-evaluated, which further adds to the pressure on the business. UES was seen as a possible solution.

As discussed in Section 2.4.4, there are a few different implementations of UES, although there are only two that are in relatively widespread use. For this study, an established commercial off-the-shelf UES system known as 'Pundit/CMM®' was selected (Baldwin et al., 2007). However, prior to carrying out a 'virtual measurement systems analysis', the software would require validation. Indeed, ISO 15530-4 (2008) provides a cautionary note about testing UES:

> *Given the very large number of significantly different measurands and combinations of influence factors that can occur in CMM measurements, each one of which leads to a particular measurement error that is to be compared to the expanded uncertainty as calculated by the UES, the task of testing UES is enormous.*

Thus the key question to be addressed in this study is as follows:

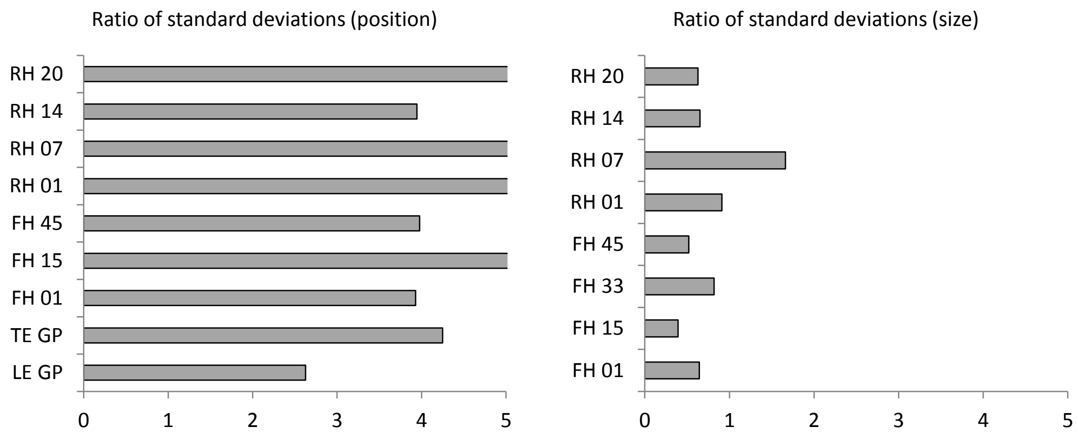
> *Is Pundit/CMM® an effective substitute for physical test for this particular measuring system, and for these specific measurands?*

5.3.2 Context-specific validation of UES

Since there was limited availability of both the CMM and the parts to be measured on it, it was decided that the first step in validating the UES would be a repeatability test. This is a simple experiment in which a part is measured a number of times; measurements on datum features that are required to align the part and machine coordinate systems are only taken once before the first run. The results give an indication of the repeatability of the measuring system, though they do not provide information about reproducibility because few variables are changed; for this, a gauge repeatability and reproducibility test could be conducted, in which factors such as the part location or time of day, would be varied. Neither was bias studied, because the manufactured dimensions of the production part were not known. Ten repeats were carried out. The tests were carried out during a working day on a production part. The results included measurements for all the key characteristics. As a by-product, measurements for the sizes of the bolt holes were also reported.

Following the repeatability test, an experiment was set up in the UES using a CAD model, the manufacturer's value for maximum permissible error, an ISO 10360 2 (2001) report showing the position of step gauges used during calibration, the results of a probe test performed during calibration, temperature records from the time of the test, and the probe patterns used for measurement. The UES was run in simulation by constraints mode, whereby the machine errors are not input into the model directly – rather limits of permissible errors are entered that are consistent with the machine specification and the ISO 10360 calibration; for each run of the simulated experiment, the UES generates a randomised error map for a virtual CMM that fits within these limits (the process is depicted in Figure 2-8). The UES provides an estimate of the mean error and standard deviation; thereby allowing predicted standard deviation, s_{sim}, to be compared with that from the physical test, s_{phys}.

The results from both sets of tests and a graphical representation of the ratio of standard deviations can be found in Table 5-3 and Figure 5-5 respectively.



	LE GP	TE GP	FH 01	FH 15	FH 45	RH 01	RH 07	RH 14	RH 20
ratio	2.6	4.2	3.9	5.5	4.0	9.3	7.2	3.9	7.3

$s_{\mathrm{sim}} / s_{\mathrm{phys}}$

	FH 01	FH 15	FH 33	FH 45	RH 01	RH 07	RH 14	RH 20
ratio	0.6	0.4	0.8	0.5	0.9	1.7	0.7	0.6

$s_{\mathrm{sim}} / s_{\mathrm{phys}}$

Figure 5-5 Ratio of standard deviations for position (left) and size (right).

Table 5-3 Results of repeatability test.

PMI	Feature	Nominal / mm	Tolerance / mm	s_{phys}	m_{sim}	s_{sim}	s_{sim} / s_{phys}
Lin	Height	101.6	±0.10	0.00088	0.00010	0.00122	1.4
Pos	LE GP	1490.90	0.30	0.00351	0.02476	0.00921	2.6
	TE GP	1473.39	0.30	0.00215	0.02443	0.00915	4.2
	FH 01	791	±0.25	0.00258	0.01725	0.01013	3.9
	FH 15	791	±0.25	0.00204	0.02507	0.01125	5.5
	FH 45	791	±0.25	0.00288	0.02614	0.01146	4.0
	RH 01	805	±0.25	0.00097	0.01564	0.00908	9.3
	RH 07	805	±0.25	0.00151	0.02334	0.01085	7.2
	RH 14	805	±0.25	0.00233	0.01611	0.00920	3.9
	RH 20	805	±0.25	0.00166	0.02754	0.01210	7.3
Size	FH 01	15.035	±0.07	0.00240	0.00003	0.00151	0.6
	FH 15	15.035	±0.07	0.00384	0.00007	0.00151	0.4
	FH 33	15.035	±0.07	0.00190	0.00000	0.00156	0.8
	FH 45	15.035	±0.07	0.00299	0.00004	0.00156	0.5
	RH 01	15.035	±0.07	0.00169	0.00000	0.00154	0.9
	RH 07	15.035	±0.07	0.00094	0.00002	0.00156	1.7
	RH 14	15.035	±0.07	0.00235	0.00001	0.00153	0.7
	RH 20	15.035	±0.07	0.00244	0.00000	0.00154	0.6

Key:				
	Lin	Linear	Pos	Position
	LE GP	Leading edge gauge point radius	TE GP	Trailing edge gauge point radius
	FH	Front bolt hole	RH	Rear bolt hole
	s_{phys}	sample standard deviation from the repeatability test		
	m_{sim}	mean error from uncertainty simulation		
	s_{sim}	standard deviation from uncertainty simulation		

The following observations can be made:

- The CMM is highly repeatable.

  It can be seen that the standard deviations obtained through physical experiment are all very low; the measure for gauge capability, C_g, as calculated according to equation [5-13], only drops below the target value of 1.33 for one of the hole sizes, FH 15, which is not a key characteristic.

  $$C_g = \frac{\mathrm{K}/100 \ \times tol}{3 \times s_{\mathrm{phys}}} \qquad [5\text{-}13]$$

  where:

  K = percentage of tolerance for calculating C_g (20% in this case)
  tol = tolerance

- The repeatability of hole positions is of the same order of magnitude as the hole size.

  On discussing the results with a measurement expert, it was commented that one might expect the hole positions to be significantly less repeatable than the hole sizes, given the location of the holes at large distances from the centre of the machine.

- The ratio of standard deviations is acceptable for the linear height measurand.

  One might generally expect the UES to overestimate since it was run in simulation by constraints mode which does not have a model of the specific set of CMM errors that contribute to the measurement error. In this case s_{sim} / s_{phys} is equal to 1.4 which is reasonable.

- The ratio of standard deviation was higher than expected for the position measurands.

  On discussing the results with the UES developers, it was learnt that one might expect a ratio of up to 3 for simulation by constraints, however the results obtained averaged at 5.9. Overestimates are expected with simulation by constraints because a model for the particular CMM is not provided. It is likely that this is related to the unexpectedly good repeatability results for the hole positions – the CMM may behave better than expected at this area of the CMM. Indeed, the CMM could have been optimised to perform best at this distance. To explore this idea, a further simulation was performed with the machine error reduced to half the manufacturer's specified value. In this case, much closer ratios (averaging at 3.4) were achieved.

- The ratio of standard deviation was lower than expected for the size measurands.

  This could be due to the fact that form error was not modelled in simulation. When the simulation was rerun with the introduction of a 5 µm random form error, the standard deviation estimates were increased in excess of the results from the repeatability test.

Although the results were not conclusive, they gave sufficient confidence in the procedure to enable the investigation to proceed to the next step, in which the measurement capability of the features under study would be predicted and analysed.

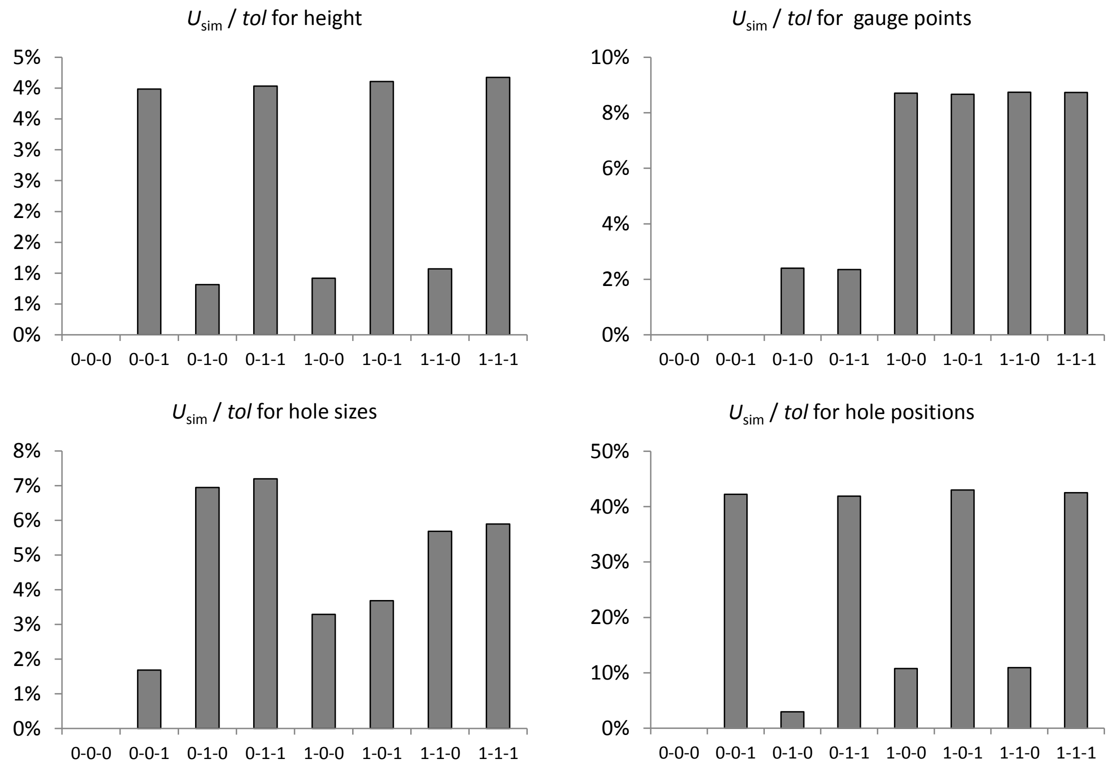
5.3.3 Measurement capability predictions

In advance of running further simulations in the UES, an indicator was agreed for use as a measure of system capability – this was to be 'uncertainty / tolerance', U_{sim} / tol. Based on the value of this ratio against each key characteristic, it was agreed that decisions would be made in accordance with Table 5-4.

Table 5-4 Use of uncertainty / tolerance indicator in decision rules.

U_{sim} / tol	Action
< 15 %	None. Measuring system is acceptable for the feature
15 % to 25 %	Borderline case. Conduct repeatability study and re-assess.
> 25 %	Measuring system is unacceptable. Discuss with design.

The UES was run eight times, setting one of more influence parameters to 'perfect' in order to help identify the key influences on uncertainty for each measurand. When reviewing the results in terms of the uncertainty / tolerance indicator, it became clear that similar measurands could be grouped together. The results of the simulations are presented in Figure 5-6.



Note: Different settings of CMM-Probe-Environment for used:
'1' indicates that the error source is included in simulation;
'0' indicates that it is excluded.
e.g. 0-0-1 means CMM and Probe were modelled as 'perfect'; temperature was imperfect.

Figure 5-6 U_{sim} / *tol* for height, gauge points, hole size, and position.

By examining the patterns in Figure 5-6, it can be seen that the main influence factors differ by measurand:

- For height, the main influence is temperature (U_{sim} / *tol* is highest when environment errors are included in the simulation);
- For gauge points, the main influence is the CMM (U_{sim} / *tol* is highest when CMM errors are included in the simulation);
- For hole size, the main influence is the probe (U_{sim} / *tol* is highest when probe errors are included in the simulation);
- For hole position, the main influence is temperature (U_{sim} / *tol* is highest when environment errors are included in the simulation).

Only for hole position is the threshold reached where the predicted measurement uncertainty occupies an unacceptable amount of the tolerance. Therefore, this was investigated further by repeating the simulation '0-0-1' for different levels of temperature uncertainty.

The results in Figure 5-7 show an almost linear relationship between U_{sim} / *tol* and temperature uncertainty for these measurands: Every 1 $^{\circ}$C of uncertainty in temperature accounts for approximately 14 % of the overall tolerance. If the magnitudes of the uncertainties predicted by the UES are accepted, it appears that it would be wise to maintain temperature uncertainty to within approximately ±1.5 $^{\circ}$C in order to keep the uncertainty / tolerance ratio below the 25 % threshold.

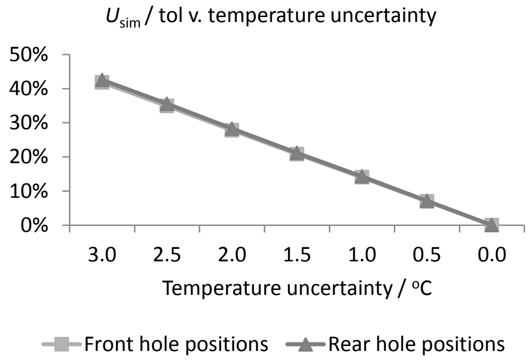


Figure 5-7 Effect of temperature uncertainty on U_{sim} / *tol* for hole position.

5.3.4 Discussion

The initial repeatability study showed that the CMM had very good repeatability (it is precise); although by its nature, such a study gives no indication of bias (its accuracy is unknown). On comparing the results from the repeatability study with estimations from the UES, some anomalies were found. It is possible to explain all of the differences, though the fact that there were differences make it difficult to defend the results from the UES with confidence. Despite this, a procedure was developed that could be used to identify high risk measurands. In order to improve upon the procedure, a number of issues need to be resolved:

- Communication of geometry

  UES software needs to be developed so that it is better linked to the design models. Significant effort was required to convert the model to a format that could be used by the UES. Additionally, assembly models could not be processed in the version of Pundit/CMM® that was used in the study.

- Usage of PMI

  The addition of PMI is sometimes problematic. In the case of the gauge points, the CAD model needed to be modified to construct a feature analogous to the real one. Clearly it is not desirable to make changes to a master engineering model in order to construct features that are only required for measurement.

- Fidelity of input data

  Simulation can only be as good as the data provided. There are two significant ways in which the input data could be improved. Firstly, the CMM could be modelled using a full parametric model; this option will be discussed in the next study (Section 5.4). Secondly, form error could be modelled which is a particular strength of the particular UES used here.

5.3.5 Study summary

In this study, the researcher attempted to carry out a virtual measurement systems analysis. This was motivated by the need for the business to conduct capability trials on a CMM which is in near constant use, and on parts which are not readily available.

Data was gathered to characterise the CMM, probing system, and environment. The model under study was loaded into the UES, together with details of the datum system and measurement plan. The UES was then used to predict the measurement uncertainties for the critical features. A repeatability study was carried out on the CMM in an attempt to validate the results from UES.

Although some encouraging results were obtained, it was not possible from this one study to gather conclusive evidence to validate the selected UES as an effective substitute for physical testing. Overall, it was found that UES has the potential to be a useful tool, though further research is required to develop a process to economically validate UES for specific CMMs and measurands.

5.4 Study 3: Validation of UES with historical measurement results

The second study uncovered technical and logistical challenges in validating UES in an industrial environment. In the third investigation, the researcher set out to address these issues by developing a procedure to make use of historical results that are already routinely collected.

The research in this section is related to another EngD that was being carried on the topic of machine tool metrology in which there was an interest in the performance of machine tools as measurement devices. Joint research was therefore undertaken and is reported in Saunders, Verma, et al. (2013). The UES analysis was performed for this EngD, whilst the findings relating to machine tool performance are related to the EngD on machine tool metrology and will be discussed in Verma (n.d.).

The study was performed using the Zeiss CMM Check®, which is designed for performing regular over-checks on the accuracy of CMMs. Measurement data was obtained from three different CMMs which are located in the same controlled laboratory in a production facility (Figure 5-8).

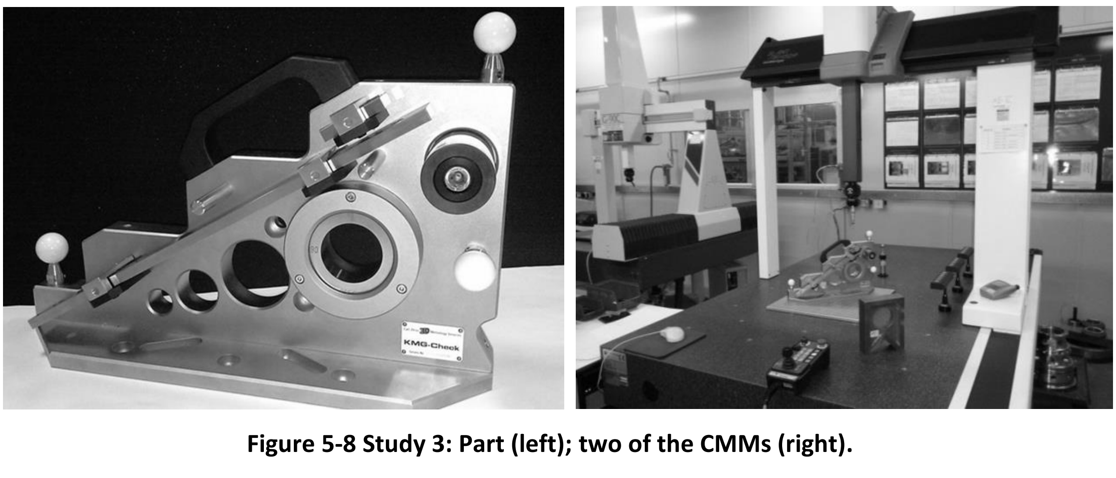


Figure 5-8 Study 3: Part (left); two of the CMMs (right).

5.4.1 Problem definition

The Zeiss CMM Check® consists of a set of calibrated gauges, comprising a ring, cylinder, three spheres, and two length bars. The artefacts are measured on a weekly basis on three moving bridge CMMs. It had been proposed to use the artefact to assess the applicability of UES for another measuring system in a different environment, thus a study was designed to first evaluate its performance for this known scenario for which a measurement history had already been built up.

The methodology can be considered a 'quasi-experiment', since the aim is to find out whether the UES would have predicted results that had already been obtained. The key question for this EngD may be framed as follows:

> *Do historical measurement results from regular performance checks validate the performance of UES in this specific industrial setting?*

Were this to be successful, it was considered valuable to develop a procedure to reuse the same artefact on a different measuring system (in this case a machine tool) in order to assess its measurement capability.

5.4.2 Comparison of measurement uncertainty estimation methods

The measurement program for each of the three CMMs was designed as follows: The top and bottom spheres were measured using nine points; the ring was measured by aligning on its planar face with eight points and then measuring a circle with eight points; finally, the cylinder was measured with two circles of eight points using the same alignment as for the ring. The length bars are also measured; however the method could not be reproduced in the selected UES.

The point sampling method used for the spheres, ring, and cylinder is shown in Figure 5-9.

Tests were performed every week on each of the three CMMs. There were over thirty data points for each CMM over a seven month period. For each test, the artefact was positioned in different locations of the CMM according to the preference of the operator. Uncertainty was calculated by applying the non-substitution method described in ISO 15530-3 (2011).

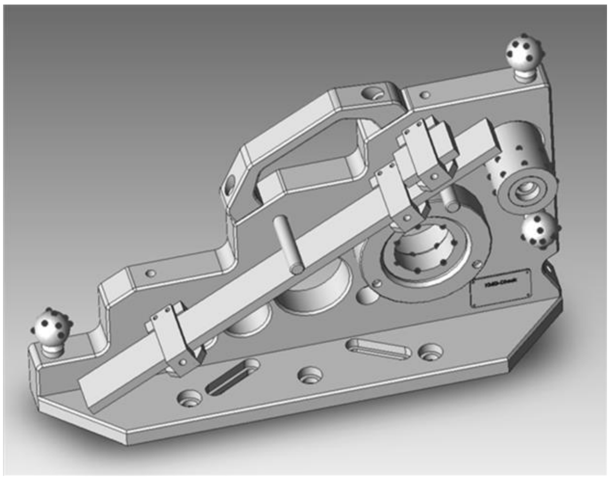


Figure 5-9 Probing patterns used when measuring the Zeiss CMM Check®.

In order to gather sufficient data to reproduce the physical test in simulation, an additional test was designed in order to characterise probing error; one hundred and twenty-five points are measured on one of the spheres of the artefact. The test has now been incorporated into the weekly test program.

In common with the second study (Section 5.3), the Cartesian errors of the CMM were modelled using performance data from recent ISO 10360-2 (2009) calibrations, rather than entering a full parametric model which would be based on the measured performance of the particular CMM. In contrast to the second study, sufficient data was now available to compare uncertainties in addition to standard deviations. Example output from the UES is shown in Figure 5-10 (although no scale is given for the Y-axis, total area is normalised to 1); Table 5-5 shows a summary of the results, presented in a format consistent with examples in ISO 15530-3 (2011).

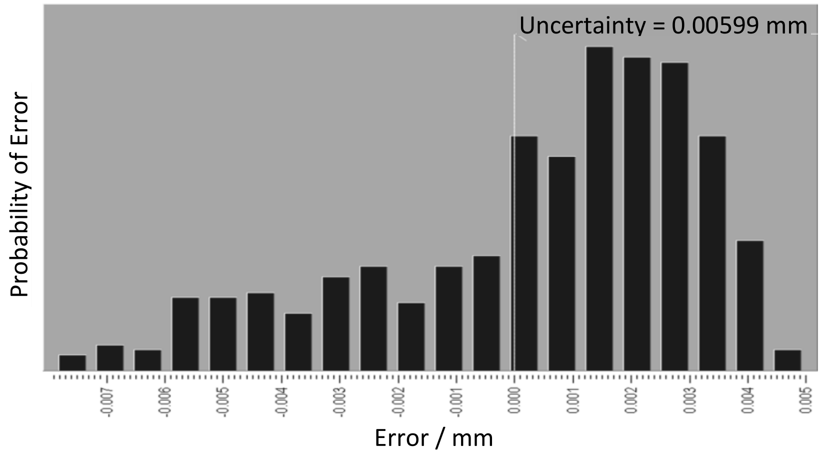


Figure 5-10 Example output from UES.

Table 5-5 ISO 15530-3 v UES predictions for ring and cylinder diameters (in mm).

	Ring (nominal 49.9983 mm)			Cylinder (nominal 50.0015 mm)		
Parameter	CMM A	CMM B	CMM C	CMM A	CMM B	CMM C
u_{cal}	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
u_p	0.00230	0.00176	0.00180	0.00159	0.00199	0.00140
b	0.00231	-0.00071	-0.00151	-0.00281	-0.00133	0.00080
u_b	standard uncertainty of the systematic error – negligible					
u_w	standard uncertainty from manufacturing process – negligible					
U_{phys}	0.0046	0.0036	0.0036	0.0032	0.0040	0.0028
$U_{phys} + \lvert b \rvert$	0.0069	0.0043	0.0051	0.0060	0.0053	0.0036
U_{sim}	0.0051	0.0060	0.0050	0.0051	0.0059	0.0050
U_{sim} / U_{phys}	0.74	1.41	0.97	0.85	1.1	1.38
s_{sim}	0.0025	0.0028	0.0024	0.0025	0.0028	0.0024
s_{sim} / s_{phys}	1.08	1.58	1.33	1.56	1.40	1.70

Key:
- u_{cal} standard uncertainty of the calibrated workpiece
- u_p standard uncertainty of the measurement procedure
- b systematic error
- U_{phys} expanded uncertainty from the non-substitution experiments (k = 2)
- U_{sim} expanded measurement uncertainty based on UES predictions (k = 2)
- s_{phys} observed sample standard deviation from the non-substitution experiments
- s_{sim} standard deviation based on UES predictions

It can be seen that the calculated expanded uncertainty (U_{phys} + $|b|$) was between 3.6 µm and 6.9 µm, whilst the estimated expanded uncertainty from simulation (U_{sim}) was between 5.0 µm and 6.0 µm. This differed from the expected result that the UES would overestimate uncertainty in every case because of the modelling assumptions the UES has to make (as discussed for the second study).

However, the instances where UES has underestimated uncertainty when compared to the ISO 15530-3 (2011) method are considered reasonable here because their magnitude is small and extrinsic factors, such as the cleanliness of the part, are not included in the simulation. Furthermore, on examining the standard deviation ratios (s_{sim} / s_{phys}), all simulations overestimated as compared to the results from physical testing (contrary to the results from the second study).

Based on these results, it was concluded that the selected UES provides valid results for the chosen measurands on this particular artefact.

5.4.3 Prediction of measurement capability using a reference artefact

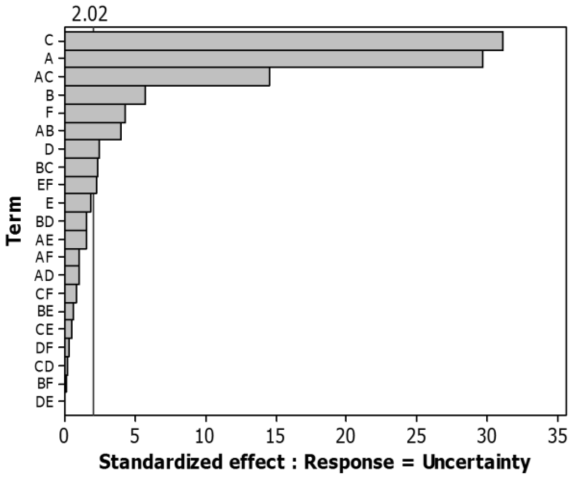
Having established the validity of UES, the next step was to attempt to develop a procedure to reuse the same artefact on a different measuring system in order to assess its capability.

In an effort to reduce error contributors that are not accounted for in the UES, it was decided to model the machine tool using the parametric mode of the UES. The parametric mode is a specialisation of the more general simulation by constraints technique, in which the constraints for the CMM are now defined by a fuller error model of the machine. The methods by which the required data was captured are unimportant to this EngD, though details can be found in Saunders, Verma, et al. (2013). More relevant here is the method which was subsequently employed to perform a virtual experiment; this was used to predict likely uncertainty contributors for the machine tool measuring system and thereby help build up an understanding of its expected capability.

A design of experiments study was carried out with the aid of the UES tool. The experiment was six factor, two level, full factorial, using the settings shown in Table 5-6. The response was the predicted uncertainty of feature size (at 95 % confidence limits), assuming a least-squares best fit; a Pareto chart of the results with second order interactions is shown in Figure 5-11.

Table 5-6 Factors in design of experiments study.

Factor	Low	High
Probe standard deviation	2.0 µm	0.5 µm
Temperature range	±2.5 °C	±0.5 °C
Machine repeatability	As measured	0.5 µm standard deviation
Sampling strategy	4 points (2 rows on cylinder)	9 points (2 rows on cylinder)
Machine accuracy	As measured (poor position)	As measured (good position)
Feature type	Ring	Cylinder



Factor	Name
A	Probe standard deviation
B	Temperature range
C	Machine repeatability
D	Sampling strategy
E	Machine accuracy
F	Feature type

Figure 5-11 Pareto chart of the standardized effects.

The low settings in Table 5-6 represent ‘average industrial conditions’, whilst the high settings represent ‘improved industrial conditions’ (borrowing terminology from ISO/TR 230-9, 2005, pp. 18–19). The sixty-four trials produced a range of uncertainty values, from 1.1 µm when all factors were set high, to 9.0 µm when all factors were set low. This compares with the uncertainty estimations of between 5.0 µm and 6.0 µm for the three CMMs, for which the UES had been shown to be a good predictor of uncertainty. In the Pareto chart (Figure 5-11), it can be seen that the uncertainty is dominated by the machine repeatability and the probe standard deviation.

In this case, it was not practical to change the dominant contributors of machine repeatability and probe standard deviation; nor could the temperature range be controlled. However, the design of experiments results suggested that it should be possible to identify an effect from varying the other factors of feature type, sampling strategy, and machine accuracy (by moving the artefact to different positions in the working volume).

In the event, the results obtained from measurement on this particular machine did not correlate well with the UES predictions. Nonetheless, the UES results did seem reasonable when compared to the manufacturer’s specification of the machine tool as compared with the CMMs. The implications of the findings related to machine tool metrology are discussed by Verma (n.d.) and in Saunders, Verma, et al. (2013). However, the contribution for this EngD is the procedure for evaluating measurement capability with the aid of UES and a reference artefact.

5.4.4 Discussion

The results from the first part of the study, when using the UES in simulation by constraints mode on conventional CMMs correlated well with historical data. The results in the virtual experiment on another measuring system seemed reasonable based on what was known about the system, although in the extreme circumstance of the UES being presented with a model of a machine tool, it appears that there may have been error sources that were missed.

In carrying out the study, it was found to be difficult to obtain all the input data required for a full parametric model. Once the data was obtained, there was not necessarily an obvious home for it within the UES. This is not a criticism of the UES implementation; rather a need for standardisation of terminology was identified in the inputs to UES, for which a start has been made in ISO 15530-4 (2008).

Perhaps the primary limitation of the study was the artefact itself. The artefact consisted of a set of calibrated gauges that were close to ideal prismatic shapes. Such an artefact may not fairly represent the measurement tasks that are carried out where form error is often a dominant factor.

5.4.5 Study summary

In this study, the researcher attempted to validate UES by capitalising on existing historical data of a reference artefact. This was a successful enterprise and gave credence to the view that the same artefact could be used to predict measurement capability on a different measuring system. A method of using the UES in conjunction with a designed experiment was developed in order to highlight uncertainty contributors that are likely to dominate.

In the discussion, it was noted that the artefact has minimal form error, and that for the procedure to be of practical use, it would be helpful to test the approach on a more representative artefact. This is the subject of the next enquiry.

5.5 Study 4: An investigation into measurement consistency

The second and third studies provided a level of confidence in UES as a tool for measurement systems analysis in an industrial environment when there is only one part. In this section, a report is made on how UES might be applied when there is variation in parts, as would be the case in a real manufacturing environment.

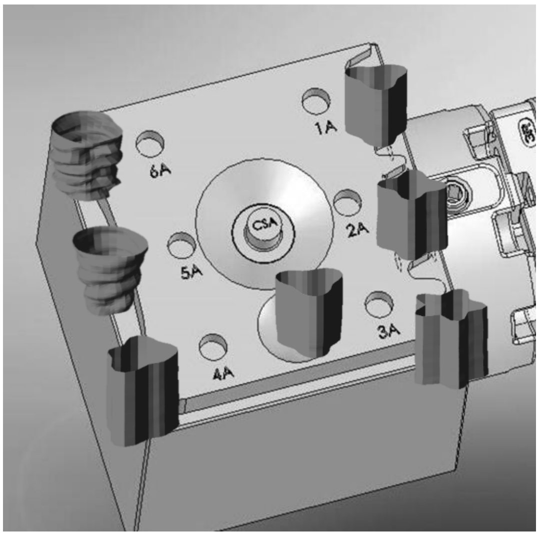
The research makes use of the Rolls-Royce multi-feature artefacts that were encountered in Chapter 4, and a pair of high accuracy CMMs located at the National Physical Laboratory. Figure 5-12 shows a schematic of Block A (top-left), a description of the form error of both blocks (top-right), and pictures of the CMMs (bottom).

5.5.1 Problem definition

Differing from the other research in this chapter, there was no immediate business problem to solve. Rather, an opportunity arose when it was discovered that the multi-feature artefacts were on loan to the National Physical Laboratory and were awaiting a purposeful study. It was felt that this was a good chance to build on the researcher’s growing experience with UES and engage the National Physical Laboratory’s world-leading resources and facilities to explore the theory of how a UES tool might be incorporated into PLM.

The purpose of the study was to address one of the most pertinent problems in measurement in industry - as components are made across many sites and by numerous suppliers, one might ask:

> *How can consistency in measurement on CMM systems be controlled?*



Feature	Block A	Block B
Hole 1	3 lobes 15 µm	3 lobes 10 µm
Hole 2	4 lobes 15 µm	4 lobes 20 µm
Hole 3	5 lobes 15 µm	5 lobes 25 µm
Hole 4	5 harmonics ~22 µm	3 harmonics ~22 µm
Hole 5	N/A	N/A
Hole 6	N/A	N/A
Boss	3 lobes 25 µm	N/A

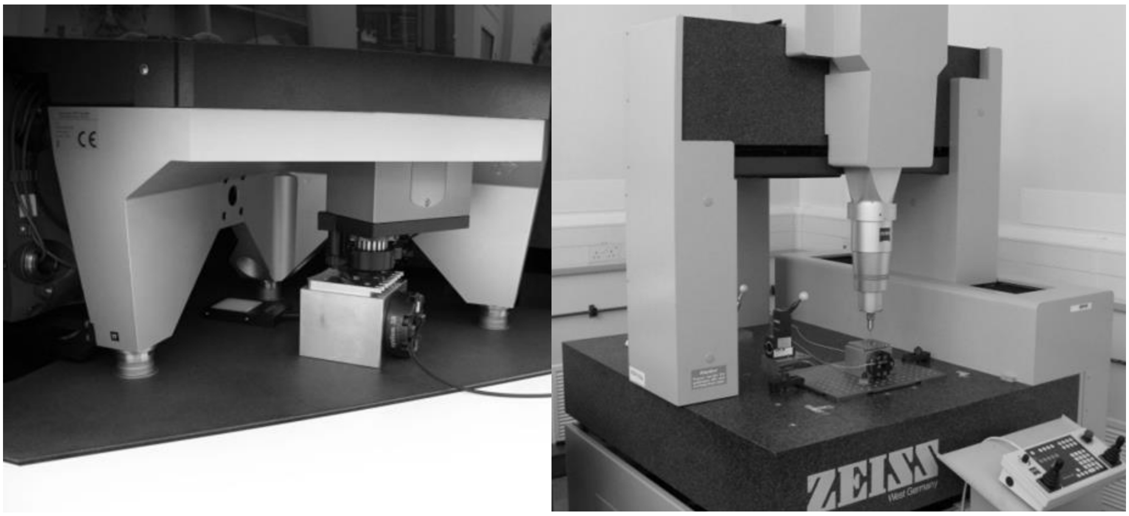


Figure 5-12 Study 4: Part (top); Zeiss F25 and Zeiss UPMC (bottom).

The desire is for both consistent results and consistent rigour.

Without systems to help control measurement consistency, one may enter unhelpful debates as to which answer is correct, or one may encounter disproportionately different costs for similar tasks. The concept of measurement consistency is first developed, before reviewing methods by which it might be controlled. A framework is then described and put into action in order to identify issues for further exploration.

5.5.2 Measurement uncertainty as a measure for consistency

A dictionary definition of 'consistency' is 'constant adherence to the same principles of thought or action' (Oxford University Press, 2014).

Whilst this definition is intended to refer to a personal characteristic, it also works well within the context of measurement when one considers that in programming, operating, and evaluating the measured points that a CMM acquires, many personal choices are made.

Recalling the sources of errors on CMM system identified from the literature in Chapter 2, three primary considerations where personal choice is paramount are as follows:

- What probing configuration will be selected?
- What sampling strategy will be employed?
- What fitting algorithms will be selected to evaluate the measurand?

There are also a large number of factors that may not lie in direct control of the CMM programmer, falling more into the realms of generic good practice. Questions might include the following:

- What are the environmental conditions of the CMM?
- What is the condition of the part?
- How well are operator procedures followed?

Given the large number of variables, it is unreasonable to expect identical results when performing measurements on different CMMs in different environments. However, for multiple results to be useful they should be consistent – they should adhere to the same principles. In order for this to be possible, the concept of measurement uncertainty can be employed. The VIM lends support to this idea in its definition of the term 'metrological compatibility' as a means of establishing whether two measurement results refer to the same measurand (JCGM 200, 2008). The VIM advises applying measurement uncertainty as a test of compatibility, by examining whether two measured values are within an agreed multiple of the standard uncertainty. The VIM's definition of compatibility is a good starting point for the requirement for consistent results from different CMM systems, although there is a need to account for the fact that when using multiple systems there will be multiple uncertainties. For consistent results, one could require that the uncertainty achieved is similar across all the CMM systems being used for any given measurand.

In order to fully satisfy the desire for consistency, rigour also needs to be addressed. In common with the definition of consistent results, it should not be inferred that the level of rigour applied to measurement, and hence its cost, should be identical across multiple systems. Rather, it should be appropriate, so that in every case the measurement process is 'just right' with the available resource. The aim should be to ensure that the uncertainty achieved for each measurand is compatible with the purpose of the measurement. If the associated uncertainty is too high, the measurement may add no value. In an extreme case, one would not choose to use, say, a steel rule to verify a length dimension that has a tolerance of fifty micrometres. Conversely, if uncertainty is unnecessarily low, one should look to see if savings could be achieved by diverting measurement resource to other activities. Again, measurement uncertainty can act as a guide to achieving consistent rigour, and ideally the uncertainty associated with every measurand would be known.

5.5.3 Measurement uncertainty manipulation

There is one uncertainty contributor for CMMs which stands out as both conceptually easy to control, and has a high influence on uncertainty – the sampling strategy. Sampling strategy is a convenient lever for measurement uncertainty, as it enables uncertainty to be changed through a mechanism that typically has a strong relationship with cost (Baldwin et al., 2010). For a CMM that uses a touch-sensitive probe to take discrete point measurements, the main components of a sampling strategy are the number and placement of the points. Typically, one would expect more points to reduce uncertainty. However, the position of those points is also significant because the optimal sampling strategy is highly dependent on form (Weckenmann et al., 1998).

Accordingly, strategies can be categorised according to the importance they place on the actual geometry produced (Moroni and Petrò, 2014), as described in the subsections below.

- Blind

  Blind strategies aim for a uniform coverage according to rules based on the nominal geometry of the feature being measured (BS 7172, 1989). These strategies are labelled 'blind', because they are only aware of the geometry specified by design; they take no account of deviations from nominal that are introduced in manufacturing.

- Expert

  A small number of knowledge-based systems have been devised that attempt to capture the knowledge of experts (e.g. Hwang et al., 2002). This may include knowledge of the manufacturing process. However, given the large number of variables involved, doubts have been raised as to whether information captured can ever suffice (Moroni and Petrò, 2011, pp. 150–151).

- Adaptive

  The trend is towards strategies that adapt to real geometry. Innovative approaches that alter the strategy dynamically, using prior measurements to drive the choice of the next point, are promising (Ascione et al., 2013). However there are unresolved technical difficulties, for example in avoiding collisions. A related adaptive approach is to study the manufacturing process and characterise its 'signature', which can be defined as the pattern of geometric deviations that are most typically produced (Moroni and Petrò, 2011, p. 132). The signature is used to develop a model of the real feature that was produced. Measurement strategies are then devised based on this model of the real feature.

5.5.4 Framework for measurement consistency

Common practice for designing the sampling strategy is to make use of the advice in *CMM Measurement Strategies* (Flack, 2001). This guide is issued by the National Physical Laboratory, the guardians of measurement standards in the UK, and this particular publication is widely used internationally. Whilst the majority of the document is devoted to blind strategies, the guide advises that it is better to develop an adaptive strategy, based on an analysis of the manufacturing process signature, labelling the two approaches as 'ad hoc' and 'scientific' respectively. The scientific approach is adaptive in nature, and the researcher believes that it could be enhanced by considering it within a PLM context. A theoretical framework that shows how the scientific method could be implemented as a means to control consistency is presented in Figure 5-13.

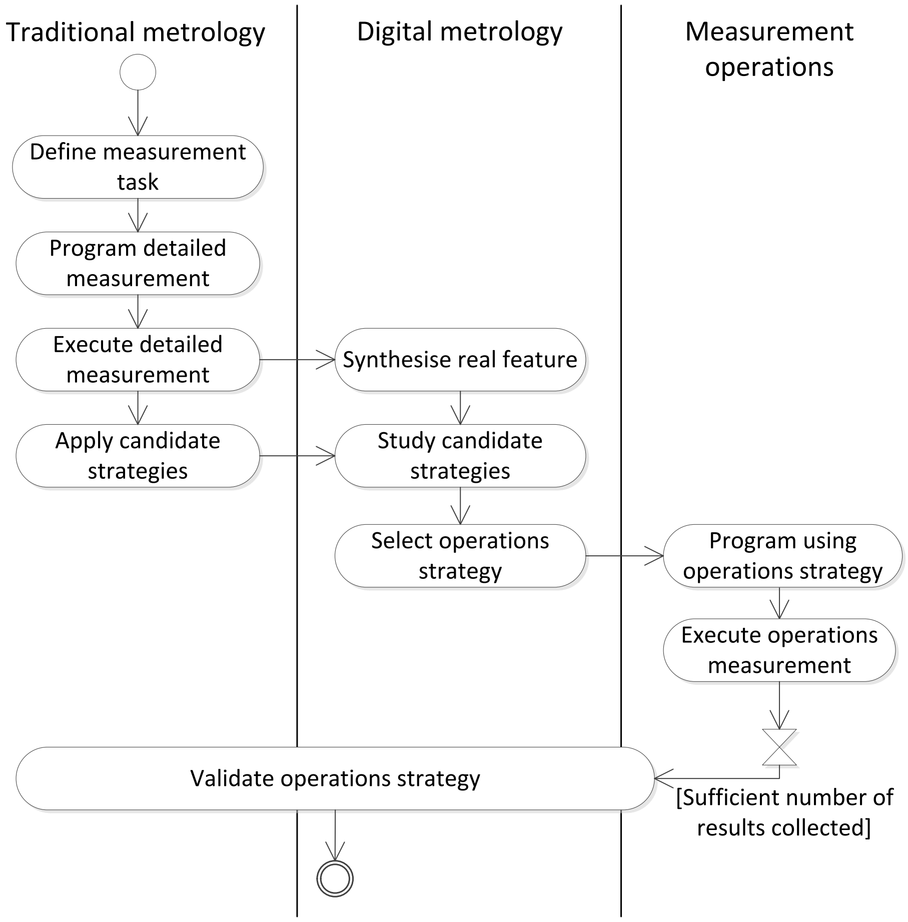


Figure 5-13 Activity diagram for controlling measurement consistency.

- Measurement operations

  Finally, automated programming packages exist that offer ways of implementing the measurement strategies. By using standard programming interfaces, they provide the mechanism by which measurement strategies can be deployed on a variety of machines. However, a challenge remains in validating the success of the operations strategy; will it be sufficiently robust to spot change in manufacturing output? This will be discussed in the context of the experiment outlined in the next section.

5.5.5 Implementation of the measurement consistency framework

In this section, an attempt is made to follow the process shown in the framework, investigating the ability of an operations strategy to spot changes in manufacturing output.

- Define measurement task

  The study is centred on the two artefacts that were manufactured with deliberate form errors, as illustrated and described in Figure 5-12.

Cylindricity was selected as the geometric tolerance to evaluate because it is expected to be particularly sensitive to sampling strategy.

Two CMM systems were employed: One for the ‘detailed measurement’; the other for the ‘operations measurement’. Key parameters of these systems are listed in Table 5-7; the maximum permissible error for the CMM and probe errors were obtained from VDI/VDE 2617 and ISO 10360-2 (2009) performance tests for the respective CMMs. Both systems were used in discrete point mode.

- Program and execute detailed measurement

  The detailed measurement was performed on a Zeiss F25 CMM (Leach, 2010, pp. 273–274); it was programmed using Calypso software (Carl Zeiss Industrial Metrology, 2013). The blocks were aligned using seventy-eight points to construct the top plane (datum A), twenty points for a line on a side plane (datum B), and one hundred and twenty-eight points to obtain the centre point of hole 5 (datum C). Hole 5 was selected as a datum because it had no deliberate form error. The boss and the holes were measured using sixty-four points at four levels (256 points in total).

  The measurements were repeated twelve times in two different orientations to give a mean and standard deviation for cylindricity, *γ*, defined as the distance between two coaxial cylinders which contain the measured points using Calypso’s Chebyshev minimum zone algorithm. The standard deviation was found to be 0.1 µm or less for all seven features on both of the blocks; consequently the measurements were considered to be sufficiently repeatable to allow further analysis based solely on the mean.

- Synthesise real feature and apply candidate strategies

  The measured points from one of the measurement runs were plotted in order to visually confirm the manufacturing signature according to the form error described in Figure 5-12. The plots correlated well with measurements that had been made previously using a similar environment at a different location and time (Lobato, 2011, pp. 3/3–36). An example of the results achieved at one of the four levels for the central boss on Block A is shown in Figure 5-14. Metrosage Pundit/CMM® v4 was selected as the UES because it has the ability to model form error (Baldwin et al., 2007). The form was described for each feature through the user interface. Relevant performance parameters for the operations environment were also input to the UES, along with details of the less rigorous sampling strategy of eight points at four levels for feature measurement, as outlined in Table 5-7. The alignment strategy remained unchanged.

- Study candidate strategies and select operations strategy

  The UES showed that there would be a ‘penalty’ for this reduced strategy in the operations environment of between 1 µm and 1.6 µm for each feature; the penalty is the increase in measurement uncertainty associated with the operations strategy and CMM. Assuming a cylindricity tolerance of 20 µm, and a 10:1 ratio between the tolerance and an acceptable increase in uncertainty, this might be deemed to be a reasonable price for measurement on a less costly system.

- Program and execute operations measurement

  Next, the operations measurement was performed using a program that was developed in Calypso; it was executed ten times in two orientations. On analysing the results, it was found that there were two instances where the standard deviation reached 0.5 µm and 0.3 µm (Hole 5A and 3B respectively); for all other cases, the standard deviation was less than 0.2 µm, providing confidence in the repeatability of the system.

- Validate operations strategy

  The Calypso software for the Zeiss UPMC CMM was equipped with a virtual CMM (VCMM) (Trapet et al., 1999), so the program was also run in VCMM mode; the VCMM reported a maximum uncertainty of 0.2 µm. The small number reflects the fact that this VCMM does not model form error, and provides further support for the thinking that the interaction between form and strategy is likely to be a major source of any major differences in cylindricity.

  Table 5-8 lists the mean cylindricity calculated for each feature from the detailed and operations measurements. The parameter η is an indication of how much form was captured by the operations measurement as compared with the detailed measurement.

Table 5-7 CMM systems at the National Physical Laboratory.

	Detailed	Operations
CMM	Zeiss F25	Zeiss UPMC 550
Maximum permissible error (1D for UPMC)	0.25 µm + L/666	0.9 µm + L/300
Probe error	~0.25 µm	~0.6 µm
Temperature range	20 ^{o}C ± 0.05 ^{o}C	20 ^{o}C ± 0.1 ^{o}C
Strategy	256 points (64 @ 4 levels)	32 points (8 @ 4 levels)

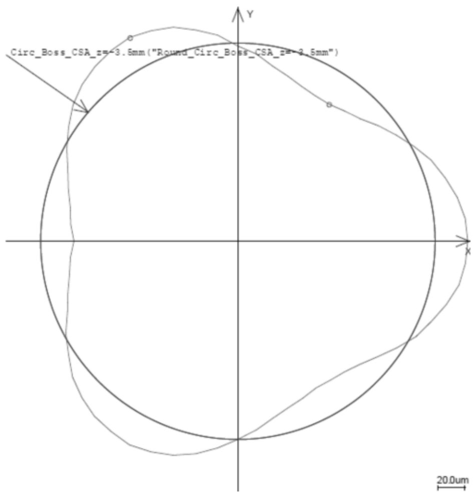


Figure 5-14 Plot showing 25 µm amplitude 3-lobe form error on boss.

Table 5-8 Percentage of form captured.

	Block A			Block B		
	γ_{de} / µm	γ_{op} / µm	η (γ_{op} / γ_{de})	γ_{de} / µm	γ_{op} / µm	η (γ_{op} / γ_{de})
Hole 1	32.8	25.3	0.77	19.9	17.2	0.86
Hole 2	32.5	33.5	1.03	41.3	41.3	1.00
Hole 3	34.8	26.0	0.75	49.9	41.8	0.84
Hole 4	35.8	27.0	0.75	31.4	24.3	0.78
Hole 5	7.1	5.0	0.70	4.4	4.2	0.97
Hole 6	2.1	2.1	1.00	4.7	4.0	0.84
Boss	52.0	48.8	0.94	1.9	2.5	1.30

Key: γ_{de} Cylindricity from Zeiss F25 measurements ('Detailed')
γ_{op} Cylindricity from Zeiss UPMC measurements ('Operations')
η Proportion cylindricity captured in Operations compared to Detailed

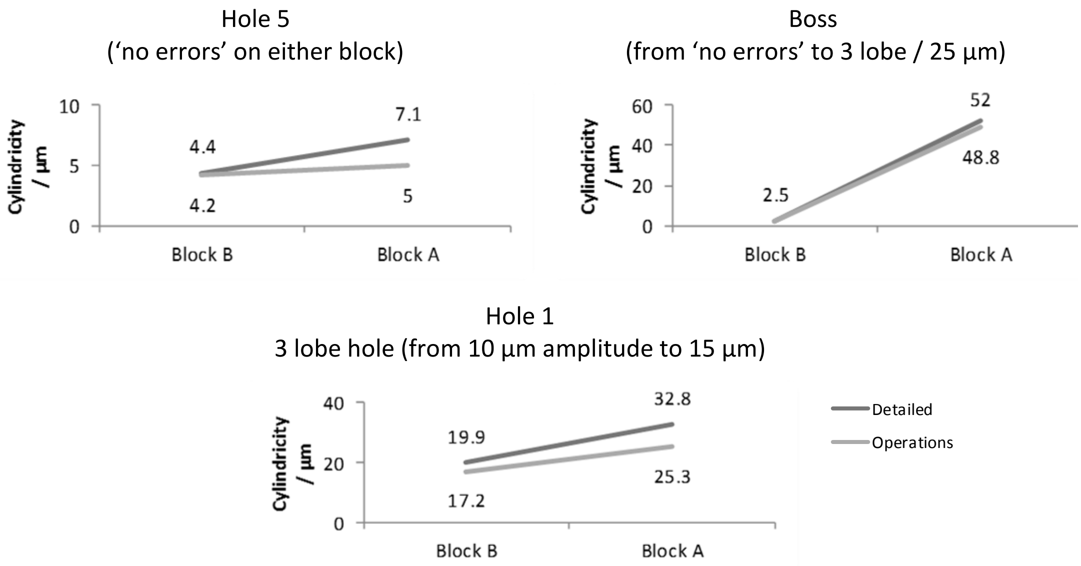


Figure 5-15 Reported cylindricity from alternate CMMs systems.

5.5.6 Discussion

The purpose of the study was to identify whether a strategy that is verified with the aid of UES can be sufficiently robust to spot change in manufacturing output, which is a key goal of measurement. By reviewing the results, a number of observations can be made.

- Relationship between form and sampling strategy

  In general, the results in Table 5-8 validate the theory that by taking fewer measurement points, less form is picked up. In some cases, such as Holes 3 and 4 on both blocks, the effect is in the order of 8 µm which could make the difference between a pass and fail in a precision manufacturing environment.

  However, there were two features for which the operations environment reported higher cylindricity than when performing the detailed measurement: Hole 2 on Block A and the Boss on Block B. There are at least two explanations for these seemingly counter-intuitive results. Firstly, at 1 µm and 0.6 µm respectively, the differences are small enough that they could be accounted for by an accumulation of measurement errors. Secondly, in the case of Hole 2, the number of points chosen in both the detailed and operations environment was a multiple of the number of lobes on the hole; it is therefore possible that similar high and low points were found using both strategies. This effect is well documented in the literature, and it is usually recommended that a prime number of points are taken (BS 7172, 1989).

- Measurement consistency for stable measurands

  Also observable from Table 5-8, and as visualized for Hole 5 in Figure 5-15, it can be seen that for the holes that had no deliberate errors, the highest observed mean cylindricity was 7.1 µm for the detailed measurement. The largest difference for this category of hole, as compared to the operations measurement, was 2.1 µm. Thus, the results from the detailed and operations systems correlate well where no significant form error is present.

- Measurement consistency for unstable measurands

  Having established that there appears to be a strong relationship between form and sampling strategy in this experiment, and that an operations strategy can be effective in a situation where there is little variation in the form induced by manufacturing, one might ask how effective a sampling strategy would be in the face of changing manufacturing output?

  The change in the form of the boss was clearly identified by the operations strategy, as seen in Figure 5-15. In this instance, the large and sudden change from a feature that had no deliberate errors, to one in which a 25 µm error had been induced on three lobes, is clearly observable in the result. However, it is less clear that the operations strategy would be effective in a situation where the change is less pronounced. For example, Hole 1 in Figure 5-15 shows a scenario where the amplitude of a three lobe error has increased from 10 µm to 15 µm. The detailed measurement clearly spots the change; however the result from the operations measurement is less definitive (8 µm difference as opposed to 13 µm for the detailed strategy).

- Measurement consistency when operating at the margins

  Theory supports the idea that one should be able to use sampling strategy as a lever for measurement uncertainty. By making use of uncertainty evaluating software, it should be possible to identify context-specific strategies to provide consistency in measurement across the supply chain. The results from the case study are encouraging, though they also highlight potential dangers when manufacturing output is subject to subtle changes. Unfortunately, economic pressures will tend to force manufacturers to employ measuring systems that are only marginally capable (Orchard, 2011b).

Potential mitigations include repeating the detailed measurement at regular intervals to identify when there has been a change in form of sufficient magnitude to warrant a change in the operations strategy. This is recommended in the National Physical Laboratory's guidance on the scientific approach (Flack, 2001, pp. 39–42), though assumes there is sufficient volume. Alternatively, in a medium volume environment, one might apply a systematic jitter to the strategy. There could be resistance to employing such an approach in highly-regulated environments; however, if found to be effective, the approach should be considered. Perhaps the most desirable option would be to simulate manufacturing variation, and test strategies against a range of manufacturing outcomes when making measurement uncertainty predictions, although this could result in overly conservative measurement strategies.

- A systems perspective on measurement consistency

  Thus far, the discussion has stayed within the confines of the measuring system. However, the key benefit of the proposed framework for controlling measurement consistency could be in opening discussions with manufacturing and design. For example, if no operations strategy can be found that allows measurement uncertainty to be maintained within desired boundaries using available resources, a more appropriate solution may lie outside of measurement. It may be the case that manufacturing process could be modified so that the output is more stable; alternatively, there may be scope for a tolerance to be loosened; or a design change could be implemented to avoid the need for measuring the 'unmeasurable' feature.

5.5.7 Study summary

The question that was posed for this study was whether measurement consistency on CMMs could be controlled. A framework was described whose origins are rooted in an authoritative CMM good practice guide. The experiments that were performed were not intended to be exhaustive, but rather a means to highlight issues. Both the detailed and operations strategies were performed in well-controlled environments at the National Physical Laboratory, and the CMM systems had only slight differences in capability. The results obtained exhibited high levels of repeatability. Whilst the question could not be fully answered, the framework appeared to have merit – uncertainty could be manipulated, and thus consistency could be controlled, to some extent in this laboratory environment.

However, the scope of the study was restricted to a relatively small number of measurands, and some limitations should be noted as follows:

- All measurements and simulations were carried out in discrete point mode. Scanning was not considered, even though this is an increasingly well-used mode of measurement in industry. Similarly optical probes and other types of coordinate measurement, such as laser trackers and measurement arms were not addressed. However, only discrete point measurement on CMMs is modelled in the simulation tool that was chosen.

- Cylindricity would normally be evaluated using many more points (Henzold, 2006, pp. 242–249). In fact, scanning or the use of another special-purpose measurement machine might have been more appropriate. However, recall that the intention of the study was to explore the effect of strategy on uncertainty, for which the study of cylindricity is well suited.
- The regularity of the form error on the artefacts may not necessarily be a fair representation of manufacturing output.
- The framework would indicate that a variety of candidate strategies should be developed, to allow selection of the most appropriate one. In this study, only one candidate was developed.
- It would have been useful to study the results on more CMM systems.
- The integration of UES with other uncertainty evaluation techniques was not investigated.

Given these limitations, it was determined to continue with the investigation and include the following:

- More measurands (features, characteristics, and less regular form error);
- More strategies (at differing levels of rigour);
- More CMM systems (at differing levels of accuracy);
- Enhanced uncertainty evaluation through integration of other techniques (especially measurement history).

All of these items are addressed in Chapter 6.

5.6 Summary

In this chapter, four interrelated studies were reported. They were targeted at live business problems (for the first three), or motivated by a business opportunity (for the last case).

The first study explored process capability indices:

> *Can the variation due to measurement be de-coupled from the observed C_{pk} in the context of this industrial setting?*

The starting position, agreed with the project stakeholders, was that in an environment where measurement data is plentiful there should be sufficient information available in order to disentangle the influence of measurement variation from process capability without recourse to further physical studies.

A procedure was developed to make use of GRR results, though such data was not as available or as current as one might have expected prior to the intervention. Doubts could also be raised as to whether such data sufficiently covers the sources of uncertainty that would be encountered in production. Thus, the research was driven towards the use of uncertainty simulation software.

The second study tackled the problem of measurement systems analysis on a large CMM:

> *Is Pundit/CMM® an effective substitute for physical test for this particular measuring system, and for these specific measurands?*

A procedure for carrying out a virtual measurement systems analysis using a particular implementation of UES was developed. Emergent outcomes from the study included recommendations for improvements to the UES, most of which have now been addressed. However, despite encouraging results it was found to be problematic to prove the validity of UES in this specific context without conducting extensive physical experiments.

As for the first case, it was not deemed to be economically viable to conduct the necessary trails. Thus, a less intrusive approach was sought for the third case.

The third study was used as a vehicle to answer the question:

> *Do historical measurement results from regular performance checks validate the performance of UES in this specific industrial setting?*

It was shown that UES results correlated well with results from physical tests for an artefact with idealised geometry. In addition, a procedure for using UES in conjunction with a designed experiment was developed in order to highlight uncertainty contributors that are likely to dominate.

It was noted that the artefact has minimal form error, and that for the procedure to be of practical use, it would be helpful to test the approach on a more representative artefact. The idea is that a known physical artefact and process for which UES has been found to be valid in one measuring system could be taken to validate the UES for a second system.

Finally, in the fourth study, a wider challenge was taken on:

> *How can consistency in measurement on CMM systems be controlled?*

This question allowed the researcher to build on experience from the previous cases and explore the ‘wicked’ problem (as discussed in Section 3.4.3) of measurement consistency. In this case the term ‘measurement consistency’ was developed as a means to describe the goal of achieving comparable levels of measurement uncertainty when using different measuring systems.

A framework was introduced by which measurement consistency can be controlled on CMMs in a PLM environment. The framework builds on the ‘scientific approach’ for developing a sampling strategy (Flack, 2001, pp. 39–42). The experimental work showed potential in the approach, and suggested that benefits may extend beyond measurement consistency, to enable better informed discussions between measurement, manufacturing, and design.

Chapter 6 System for developing measurement standards for CMMs

6.1 Introduction

In Chapter 5, procedures for modelling the measurement capability of CMMs were created and tested, culminating in the conception of a framework for controlling measurement consistency. In this chapter, the measurement consistency framework is evolved, resulting in a system for developing measurement standards, thereby meeting the fourth objective of the EngD.

6.2 Problem definition

A commodity may be defined as a group of similar components; for example, in a gas turbine engine a turbine blade or a combustor casing might be regarded as a commodity. A measurement standard may be considered to be a reusable dataset and workflow that can be applied to ensure consistent results and rigour. Measurement standards can be usefully organised by commodity, since this defines much of the context, including design objectives and manufacturing processes.

The question to be addressed in this chapter is as follows:

> *What comprises a commodity-specific measurement standard for CMMs*?

Sampling strategy will be emphasised because it came out as an important factor during the testing of systems for PLM-enabled dimensional measurement as reported in Chapter 4.

Differing from many previous studies on sampling strategy (for example, as listed by Shilling et al., 2010), the problem is not being presented as one of optimisation. Rather, recognising that there is considerable knowledge already built into CMM measurement programs in production, the problem is defined as one of providing a means to compare the effectiveness of alternative strategies – for example, as may have been developed by different metrologists or at different moments in time. Solutions that are robust and promote consistency are favoured in preference to solutions that are theoretically optimal.

6.3 Uncertainty management concepts

In order to structure the research, the PiDM framework developed in Chapter 4 was first revised in consultation with stakeholders. The measurement planning and measurement results analysis steps within PiDM were decomposed by including ‘uncertainty management’ and ‘integrity reports’, as shown in Figure 6-1.

The rationale for modifying the framework in this way is described in the following subsections, beginning with a description of the procedure for uncertainty management (PUMA) (ISO 14253-2, 2011), before proposing how this might be simplified through the development of ‘method levels’, and how ‘integrity reports’ could be employed to monitor the effectiveness of uncertainty management and related processes.

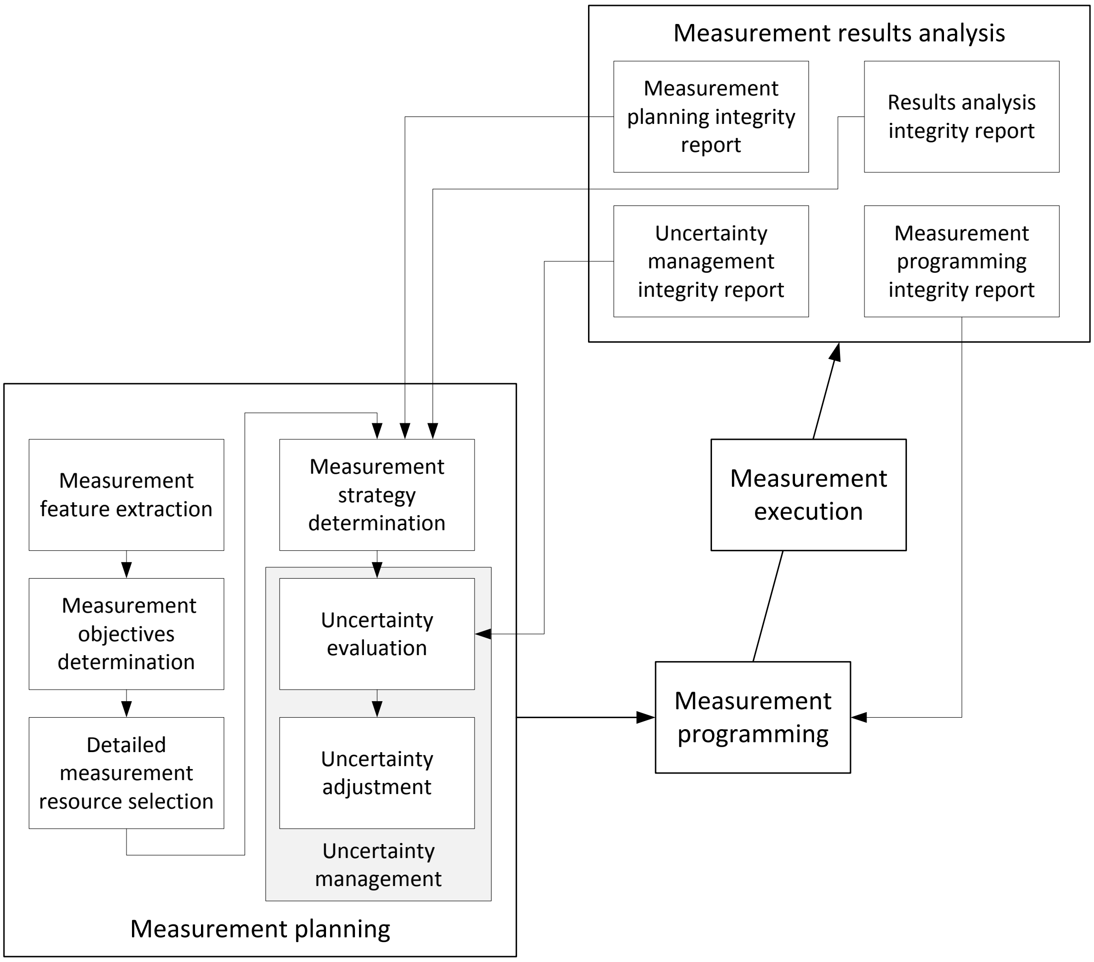


Figure 6-1 Uncertainty management in PiDM.

6.3.1 PUMA

There is little guidance from the literature on the topic of uncertainty management, despite recommendations from the standards that this is required and a growing demand from industry (Loftus and Giudice, 2014). One important exception exists in the form of PUMA, and is described in ISO 14253-2 (2011). PUMA is a procedure which was designed for estimating and managing the measurement uncertainty associated with evaluating geometric tolerances. PUMA does this by taking an iterative approach, as pictured in Figure 6-2. Having defined the measurand, measurement principle, method, procedure, and conditions, a first pass estimate is made based on a worst case analysis of any contributions considered to be dominant. This initial estimate is compared to a target uncertainty, U_T, as shown at label [A] in Figure 6-2. If the estimate is unacceptable, it may be possible to change some of the initial assumptions, or acquire additional knowledge about the uncertainty contributors [B]. If the result is still unacceptable, the method, procedure, and conditions are reviewed [C], before considering a change to the measurement principle [D], or the measuring task [E].

The parameters listed in Figure 6-2 (such as 'PMI type') are examples that the researcher arrived at after reviewing the major texts that consider dimensional measurement as a system (ASME B89.7.2, 1999; Flack, 2001; Hocken and Pereira, 2012; Zhao, Brown, et al., 2011). There are only a few such documents, as observed by Lindqvist (2011, p. 32).

Phillips (2004) raises the concern that PUMA encourages users to make unnecessarily conservative estimates of the measurement uncertainty, contrary to advice in the GUM; he also highlights the use of terminology that has not been defined in either the GUM or the VIM, such as ‘conventional true uncertainty’. Nonetheless, Phillips concedes that PUMA may find useful application within an industrial environment, and in particular when the uncertainty is not intended to be propagated into another measuring system.

However, there are only a small number of reports of PUMA being applied in the literature. These include Cebulla et al. (2004), who developed a mathematical model which uses the PUMA approach; in this source, a decision support tool is introduced that indicates the optimal number of discrete points to measure a feature given inputs regarding hardware, environment, and workpiece form error. The examples provided are theoretical and validate trends that one might expect through intuition, though have not been proven by physical experimentation. More recently, Timmermann et al. (2011) promoted the use of PUMA as part of a broader system-wide approach for implementing uncertainty analysis in production processes, though without any numerical examples to follow. It seems that PUMA is little used in industry, perhaps because it may be perceived as time-consuming, difficult, and therefore costly to follow, particularly when applied to CMMs. For instance, the author was unable to find examples of PUMA being employed for CMMs within Rolls-Royce plc despite explicit sanction for its use within company procedures.

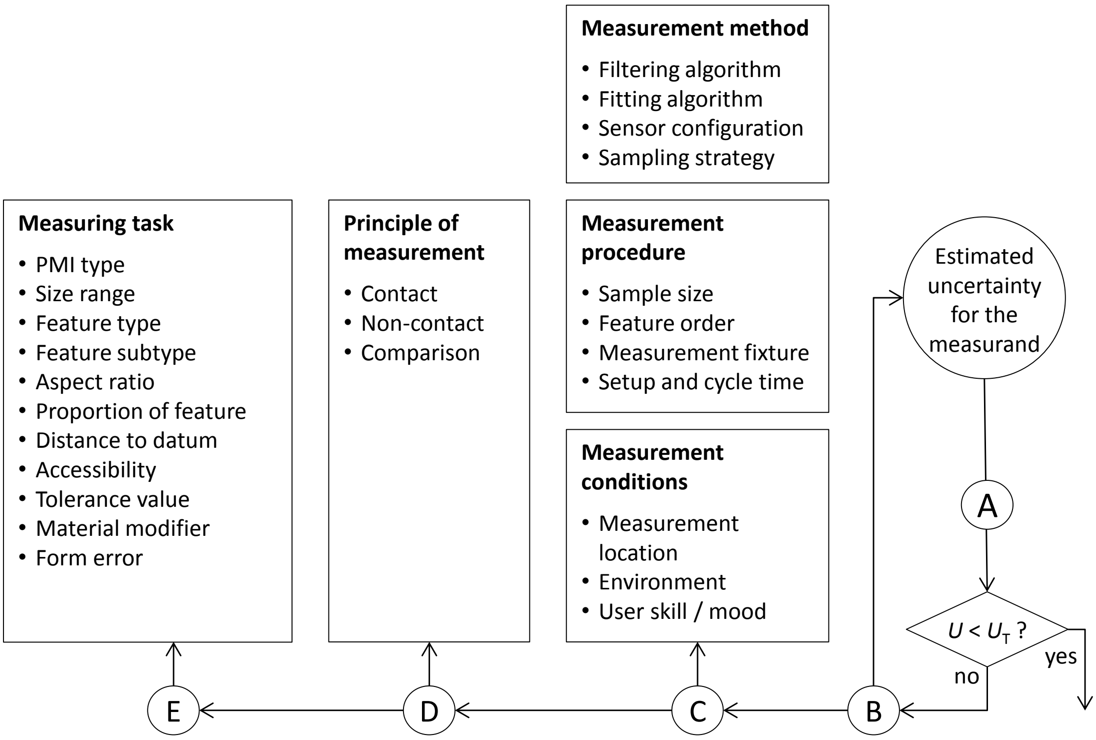


Figure 6-2 Schematic of PUMA – based on ISO 14253-2 (2011)**.**

6.3.2 Method levels

One major source of complication is that there are many factors to consider; over one hundred and sixteen uncertainty contributors are listed in the standard where PUMA is described. Many of these contributors are correlated, adding to the difficulty of analysis. The author believes that the total uncertainty model described in ISO 17450-2 (2012) (Section 2.5.2) can be applied to simplify PUMA; in this model, measurement uncertainty, which is the focus of PUMA, is made up of method uncertainty and implementation uncertainty. Method uncertainty relates to differences between the methods chosen to verify a part and the way in which it was specified; whereas, implementation uncertainty is concerned with the execution of the measurement act itself. Accordingly, a simplified version of PUMA is proposed, as illustrated in Figure 6-3; 'measurement method', 'measurement procedure', and 'measurement conditions' are replaced with 'method level' and 'implementation level'.

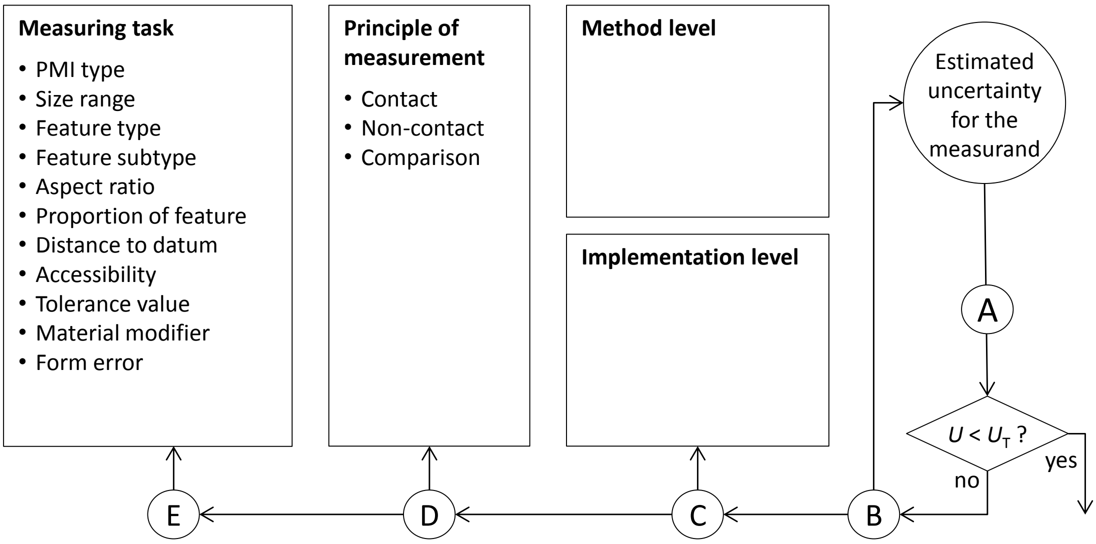


Figure 6-3 Simplified version of PUMA.

The implementation level is intended to correspond to those factors which influence implementation uncertainty. An example would be the specified accuracy of the CMM hardware and probing system, or the closeness of agreement between results from a fitting algorithm used by CMM evaluation software as compared to a reference result from using best-in-class algorithms. Thus an implementation level can be thought of as a set of measurement process parameters that achieve an implementation uncertainty within a specified range; a high implementation level would imply a low implementation uncertainty.

Similarly, a method level will be defined as a set of measurement process parameters that achieve a method uncertainty within a specified range. For example, even if the implementation of an evaluation algorithm is good, the choice of algorithm may not accord with the specification from design; in this case the method level would be low. In the case of sampling strategy, methods might vary from the most rigorous to that more akin to common practice for non-critical features, such as measuring four discrete points to evaluate the size of a hole.

An important source of method uncertainty arises from the interaction between the component and the measurement device (Section 5.5.3). Since the focus of this research is on *commodity-specific* standards, with an emphasis on sampling strategy, it is method uncertainty that is of most interest. Implementation uncertainty will be assumed to be 'good' and meet general good practice.

6.3.3 Integrity reports

In order to test the effectiveness of the CMM measurement standards which will be developed, integrity reports are also proposed.

The integrity report will be used to assess the completeness, rigour, and appositeness of a process: Completeness can be defined as the degree of coverage; rigour is satisfied when a process is deemed to be theoretically correct; lastly, a process is considered apposite when it balances all competing requirements appropriately.

The aim of the integrity report is to characterise the effectiveness of a particular step within the measurement process. A single metric is proposed for each aspect of the report, as shown in Table 6-1.

Table 6-1 Metrics for integrity reports.

Integrity type	Completeness	Rigour	Appositeness
Measurement planning	% Planned PMI *objective is 100 %*	$\lvert U - U_T \rvert$ *objective is zero*	An acceptable cost *objective is zero*
Uncertainty management	% Managed PMI *objective is 100 %*	Validity of estimation method *e.g. see guidance in ISO 15530-4 for UES*	A pragmatic choice of UES inputs *qualitative metric*
Measurement programming	Degree of functionality in the CMM program *qualitative metric*	Conformance of CMM program to plan *qualitative metric*	A pragmatic level of optimisation in the CMM program *qualitative metric*
Measurement results analysis	Traceable results with uncertainty *qualitative metric*	Provision of data for other processes *qualitative metric*	Utility of integrity reports *qualitative metric*

For a complete measurement plan, one might expect that all the measurands should be considered. Whilst for rigour, it is necessary to ensure that the target uncertainty is achieved for every measurand. However, there is a need to balance rigour with cost; thus a measurement plan will be considered apposite when the cost of implementing the plan is acceptable.

As with measurement planning, a complete uncertainty management process should include all the PMI in a model. Uncertainty management will be rigorous when the estimation methods used can be proved to be valid. There are numerous approaches to determining the rigour of uncertainty estimation, for example as listed in ISO 15530-4 (2008) for UES. Additionally, for the uncertainty management process to be regarded as rigorous, it is necessary to determine whether all significant uncertainty contributors are accounted for, of which there are many as discussed in Section 6.3.2. The appositeness of the process for a specific measurand is similarly challenging to assess. For the uncertainty management process to be apposite, the uncertainty contributors must be captured for an acceptable cost.

The metrics proposed for measurement programming and results analysis integrity reports are all qualitative; that is, numeric measures are not suggested in this research, though the author believes that it could be significant value in investigating these areas further. It is commonly said that no software program is ever 'finished' because there are always opportunities for improvement. This holds true for CMM programs when one considers different types of functionality that could be included, ranging from automatic probe qualification, to the ability to restart mid-program. The rigour of a program could be evaluated by considering whether it conforms to plan; for example, if a certain pattern of points was planned, how close was the implementation of this pattern within the CMM program? How closely does the chosen evaluation algorithm conform to the PMI requirement? Lastly, one might consider a CMM program to be 'apposite' if the level of optimisation is 'just right'. In the current state of art, this would be best judged by an expert.

Measurement results are only complete when they are fully traceable and include uncertainty. The amount of information required to make a result traceable is subject to debate (as discussed in Section 2.4.2), thus it is considered to be a qualitative metric. Measurement results must satisfy the needs of many other processes, such as to satisfy design requirements, to inform manufacturing, and to control the measurement process itself; rigour can only be achieved when all of these needs are satisfied. Finally, appositeness could be measured through the provision of integrity reports themselves; can useful integrity reports be delivered at an appropriate cost?

Since this chapter is aimed at developing measurement standards, rather than how they are programmed or reported, it is the integrity of the measurement planning and uncertainty management processes that are of most relevance.

6.4 Uncertainty management in PLM

6.4.1 System design

The PiDM framework, the concept of method levels, and the measures of integrity, were used as the foundations to design a system for developing measurement standards for CMMs.

The system can be described in PiDM terms. The PiDM operational contexts of data management, metrology resource management, verification and validation, and feedback (as introduced in Section 4.4.2) are shown in the column headings of Figure 6-4.

The PiDM workflow step of 'measurement planning' can now be viewed as containing four elements which are separated into rows, as follows:

1. Determine objectives

   Starting from the top left corner, the process begins by deriving a target uncertainty, U_T, to be associated with the measurement result for a specified measurand. An assessment is also made as to how the manufacturing signature can be created. For example, the signature may be known from measurement history. (The concept of a manufacturing signature was discussed in Section 5.5.3.)

2. Capture manufacturing signature

   If necessary, the relevant feature is measured in order to capture its form; there may be more than one feature related to a single measurand, such as when it is evaluated with respect to one or more datum features.

3. Estimate uncertainty

   Measurement uncertainty is estimated for a number of method levels.

4. Select method for measurand

   An attempt is made to find the most suitable method for production.

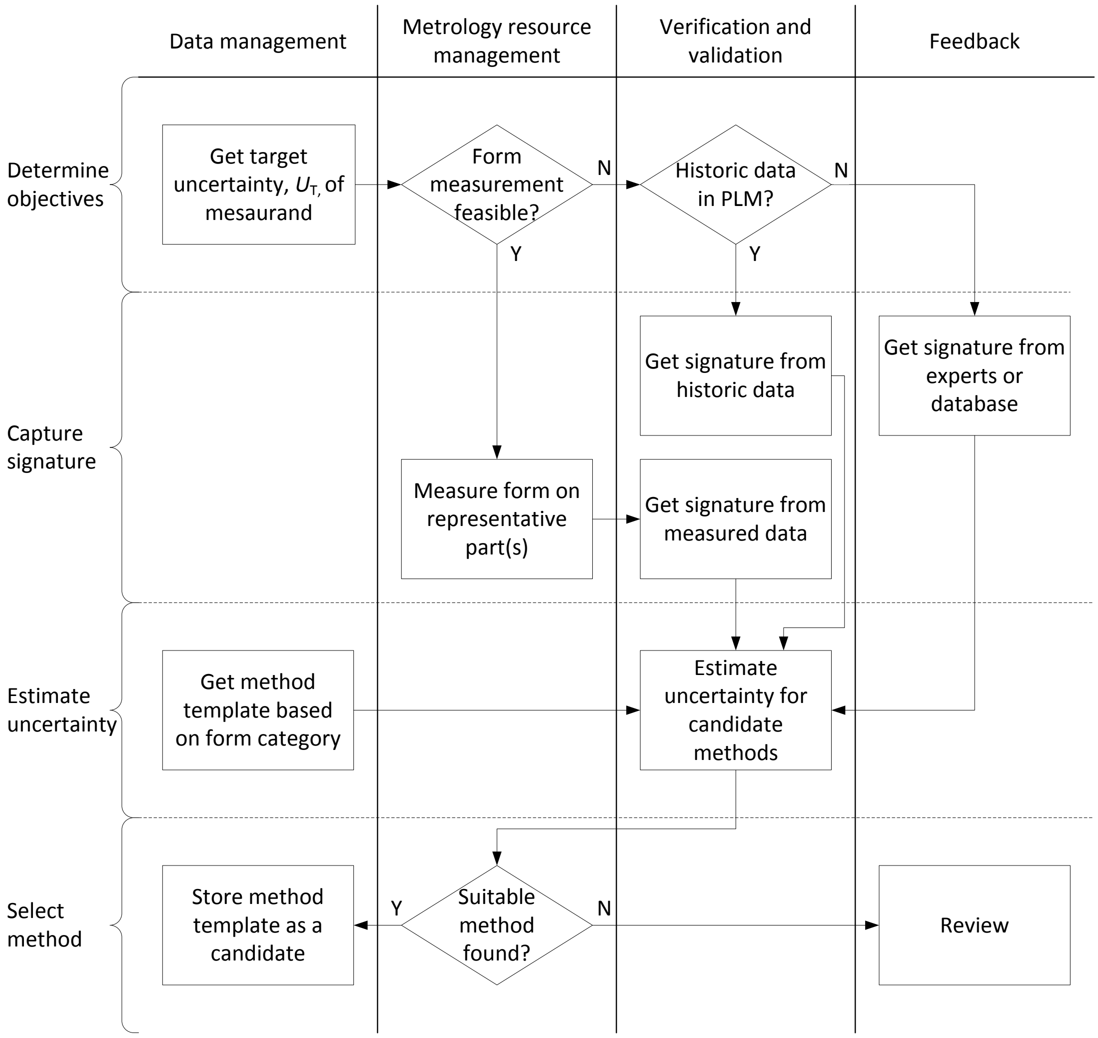


Figure 6-4 Uncertainty management in PiDM, measurand by measurand.

In common with other PiDM steps, uncertainty management is not considered to be a one-off task. Rather it is expected to be re-evaluated at periodic intervals in order to understand potential implications when, for example, a manufacturing process changes.

The system also indicates opportunities to improve estimates or return to the PMI assignment, component design, or verification and process planning steps where suitable measurement plans cannot be developed for an acceptable cost. This is shown in the box marked ‘review’, though is out of scope for the system development and testing described in the remainder of this chapter.

6.4.2 System implementation

In this section, the uncertainty management system described in Section 6.4.1 is put into action, moving from a measurand by measurand design to one which can be implemented part by part.

A template selection process was designed that was compatible with the uncertainty management system shown in Figure 6-4. In this process, method levels are managed through the use of templates in PLM. A sequence diagram that shows how such templates will be selected and used on a part by part basis (rather than on a measurand by measurand basis) is shown Figure 6-5.

The process assumes that a target uncertainty has been determined for each measurand on the part, and that the manufacturing signature will be captured by scanning. The process also assumes that UES will be used to evaluate uncertainty and that there are four method levels to be considered for each measurand:

- Level 1 Low
- Level 5 Medium
- Level 10 High
- Level 10* Reference

It is expected that three levels would be sufficient in a fully developed system, in accordance with the experience of other heuristic-based methods in current use at Rolls-Royce plc (for instance, as used within the feature verification risk analysis tool which was outlined in Section 1.4.2). The fourth ‘reference’ level is provided only as a baseline for testing. For the study reported in this chapter, only sampling strategy is varied between the levels.

The value for uncertainty predicted by UES provides information by which a decision matrix can be generated. The decision matrix lists measurands against the method levels. Where more than one measurand is related to a single feature, it is proposed that the highest level should be selected in order to measure the feature. With the decision matrix as a guide, a CMM program can be generated for the whole part.

In theory, the program should be valid for as long as the manufacturing signature remains unchanged.

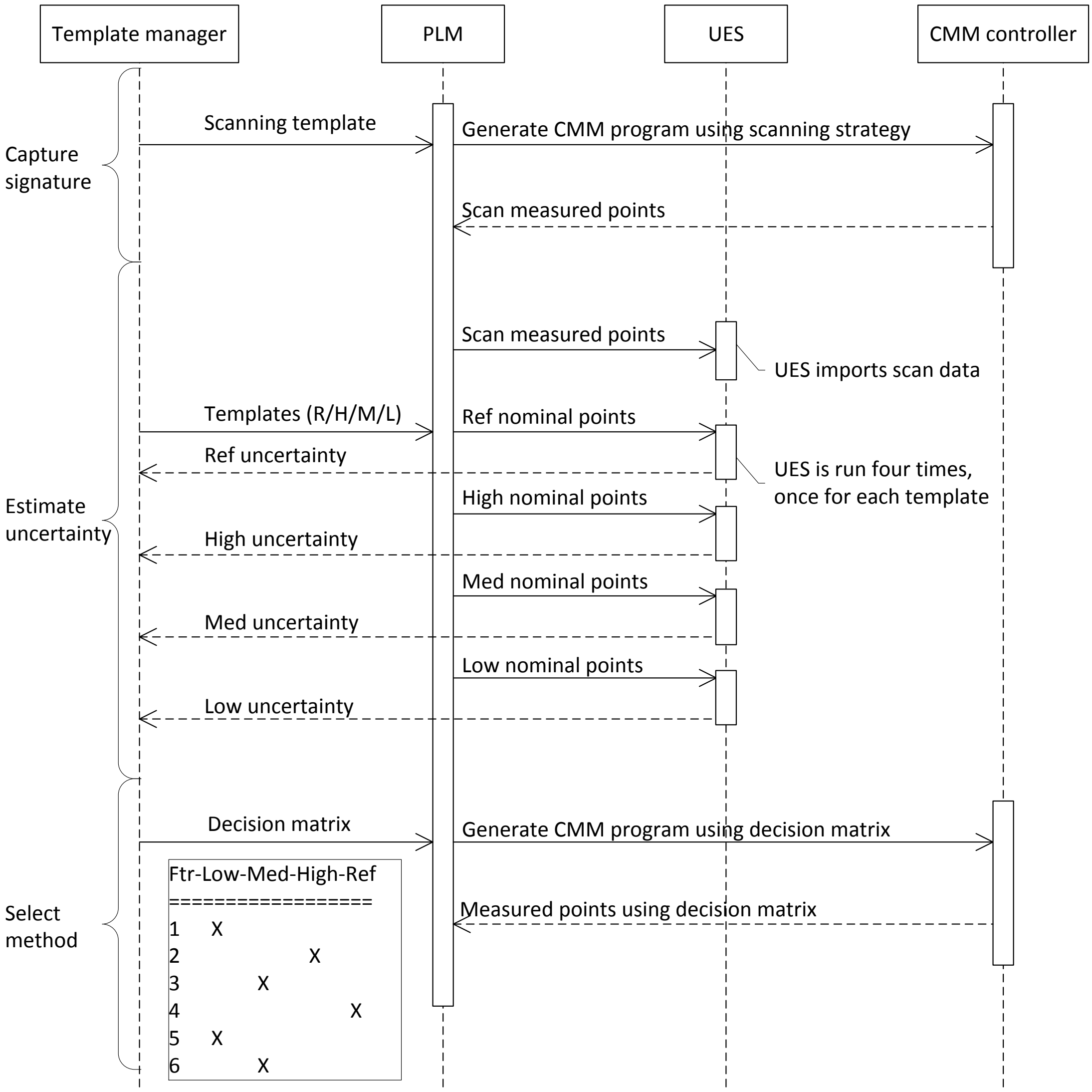


Figure 6-5 Sequence diagram for template selection process, part by part.

6.4.3 System testing

The system was tested building on a methodology developed by Frechette et al (2012). A set of complex test cases (CTC) were defined, with each CTC referring to a digital model and associated physical component. The models are defined with PMI. There are three CTCs, which are employed such that they address the following questions, which can be viewed as sub-questions for this chapter:

- Do different measurement sampling methods lead to different results?

  Results would need to be significantly different if they are to be exploited when creating measurement standards. This question is addressed in Section 6.5.

- Can reliable uncertainty statements be generated?

  Uncertainty statements would need to be sufficiently accurate and robust if they are to be relied upon to develop measurement standards. This question is addressed in Section 6.6.

- How effective is the proposed system for developing standards?

  The system will be demonstrated to investigate its validity between parts with differing PMI. The demonstration system is described in Section 6.7.

The first CTC is the Rolls-Royce multi-feature artefact which was used to validate the PiDM framework (Chapter 4), and also to develop the measurement consistency framework (Chapter 5); this CTC is used when addressing the first two questions. The other two CTCs have been developed by Aero Engine Controls and the National Institute of Standards and Technology (NIST) respectively, and will be used in the demonstration system that has been designed to address the third question. Table 6-2 shows how the CTCs are linked to the questions, and also indicates the success criteria to be used when analysing the results. The success criteria for the second and third questions are taken from the measures of integrity (completeness, rigour, and appositeness) which were proposed in Section 6.3.3.

Table 6-2 Test case objectives for PLM-based CMM measurement planning.

Question	CTC 1	CTC 2	CTC 3	Success criteria
1. Do different sampling methods lead to different results?	✓			Comparison of measured values
2. Can reliable uncertainty statements be generated?	✓	✓		Integrity of uncertainty management
3. How effective is the proposed system for developing standards?		✓	✓	Integrity of measurement planning

6.5 Impact assessment of method levels on measurement error

The first question, as shown in Table 6-2, is to assess the impact of different sampling method levels on measurement error, and builds on the investigation into measurement consistency that was described in Section 5.5. This earlier investigation had shown promise in the approach of varying sampling methods to maintain uniform levels of uncertainty in production. However, the variations that were made during the study were limited since they were restricted to just two method levels, and the study was only performed for cylindricity on high precision CMM systems. The requirement in this section is to perform a more extensive study, including more method levels and more measurands. In addition, it was thought important to widen the applicability of the research by including a less accurate CMM system, such as might be found in an industrial environment. The experiments described in this section make no reference to uncertainty simulation. Rather the motivation is to assess the impact of sampling method levels on measured values obtained under a variety of conditions.

6.5.1 Experimental design for physical measurements

Two scenarios were developed. In the first scenario a dense sampling strategy was implemented for the datum features, and the method levels were varied on the tolerance-controlled features. In the second scenario, the opposite approach was taken, as described in Table 6-3.

Table 6-3 Measurement scenarios, CTC 1.

	Feature category	Sampling strategy
Scenario 1	Tolerance-controlled feature	Variable
	Datum Feature	Fixed
Scenario 2	Tolerance-controlled feature	Fixed
	Datum Feature	Variable

The method levels were recorded in the 'template manager', as shown in the template selection sequence diagram (Figure 6-5). For the purpose of this research, this was simply a Microsoft Excel® workbook, though there is no technical reason why such templates could not have been stored within a PLM system.

The templates are specific to each feature type and are labelled as 'low', 'medium', 'high', and 'reference'. The sampling methods documented in the templates are detailed in Table 6-4 and were reviewed with experts from the National Physical Laboratory and a UES vendor; 'low' reflects common industrial practice for a non-critical feature, whilst 'high' reflects good practice for a critical feature.

In order to be able to make comparisons between the method levels, the low, medium, and high methods used a subset of the points from the reference method, as illustrated for the medium method in Figure 6-6.

Table 6-4 Sampling method levels, CTC 1.

Method level		Cylindrical feature			Planar feature
		Rows	Points / row	Distribution	Points (scattered)
1	Low	2	4	Birdcage	5
5	Med	3	5	Birdcage	11
10	High	4	11	Staggered	20
10*	Ref	4	67	Staggered	200
	Scan	20	95	Latitudinal	200+

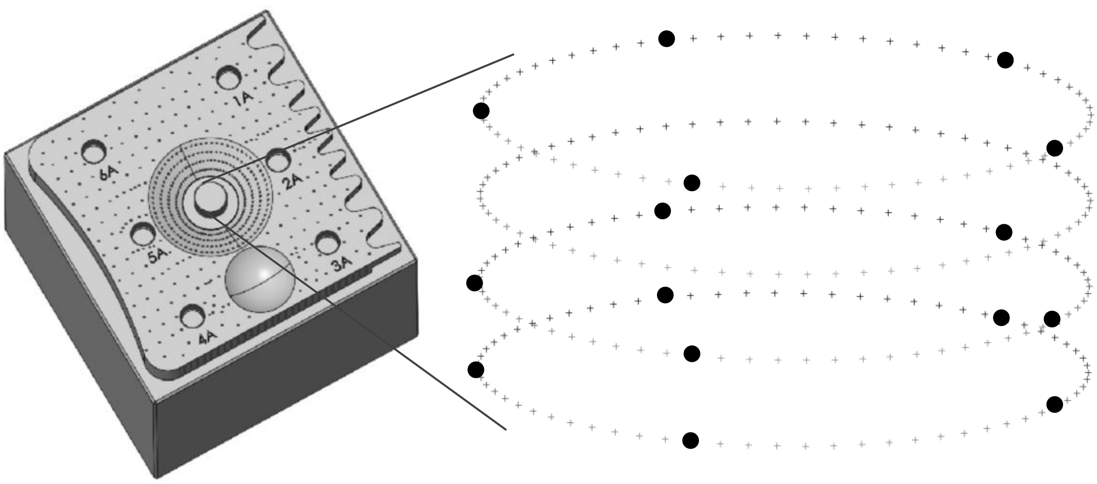


Figure 6-6 Medium method as a subset of reference on central boss, CTC 1.

An expert CMM programmer was commissioned to develop a single measurement program to apply all four of these method levels. This program took approximately one week to create.

Following a pilot run, the measurement program was run five times over five nights on a Leitz PMM-C, which is considered to be a high accuracy device. The component was removed from the CMM between runs, though replaced in the same orientation and similar location. During all measurement runs, the laboratory was stabilised at 20 ^{o}C ± 1 ^{o}C. The program took approximately four hours to run.

The entire experiment, using the same measurement program, was subsequently repeated on a Nikon LK CMM in the same laboratory. This latter CMM has a lower accuracy specification than the Leitz PMM-C and is representative of the type of CMM which is more likely to exist in many industrial environments. These two CMM systems were encountered in Chapter 4 as CMM A and CMM B (Table 4-6).

The measurement program implemented both the scenarios described in Table 6-3; the results for each scenario are reported in Sections 6.5.2 and 6.5.3 respectively.

6.5.2 Impact of varying sampling method level on controlled features

The results from five runs on CMM A and five runs on CMM B, in which sampling method level was varied on the controlled features, are summarised in Figure 6-7 to Figure 6-10; the source data is listed in Table B-2 to Table B-5.

The graphs show the average difference between the measured value obtained from the low, medium, and high method as compared with the reference method; thus it should not be considered as a performance comparison. The same scale is used on each graph.

Three observations can be made:

1. Trends are similar between the two CMM systems.

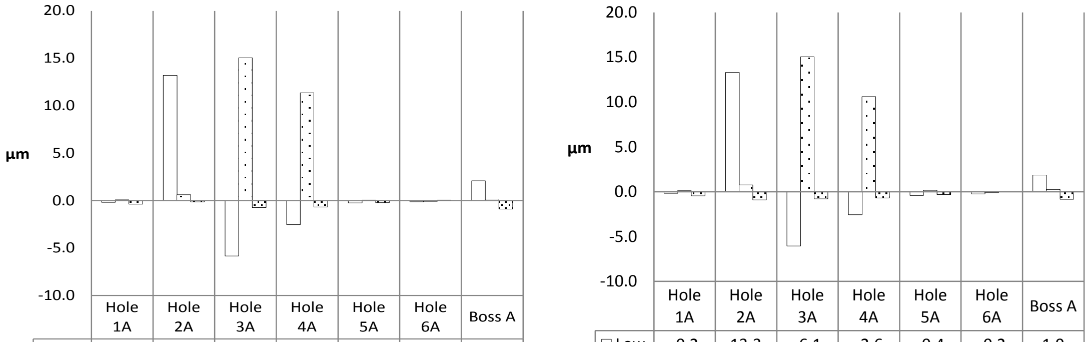
   The shapes of the graphs on the left, for CMM A, are similar to those on the right, for CMM B.

2. Sampling method levels have a more significant impact on measurement error where it is known that there is deliberate form error.

   Holes 1A, 2A, 3A, 4A, and Boss A have been manufactured with deliberate form error; these are the features for which method makes the clearest difference. All other features have been produced close to their nominal dimensions.

3. Higher method levels do not necessarily correspond to less deviation from the measured values obtained using the reference method.

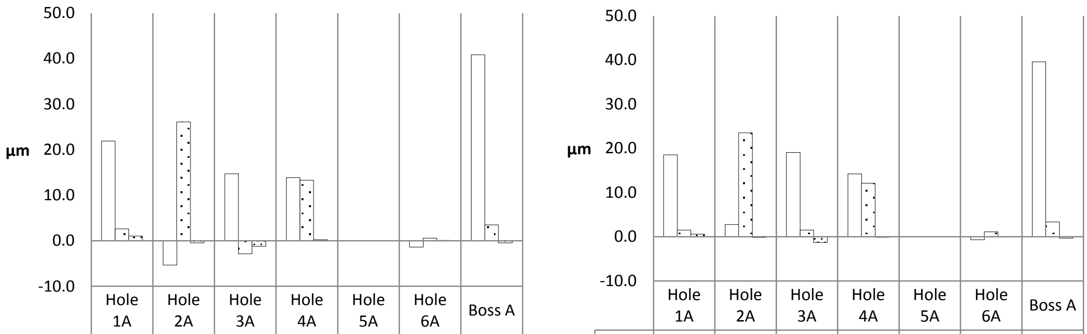
   For example, the low method for size of Hole 3A and 4A provides measured values that are closer to the reference value than obtained through the medium method (Figure 6-7).



	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-0.2	13.2	-5.8	-2.5	-0.2	-0.1	2.1
Med	0.1	0.6	15.0	11.4	0.1	-0.1	0.2
High	-0.4	-0.1	-0.7	-0.7	-0.2	0.1	-0.9

	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-0.2	13.3	-6.1	-2.6	-0.4	-0.2	1.9
Med	0.1	0.8	15.1	10.6	0.2	-0.1	0.3
High	-0.5	-0.9	-0.8	-0.7	-0.3	0.0	-0.8

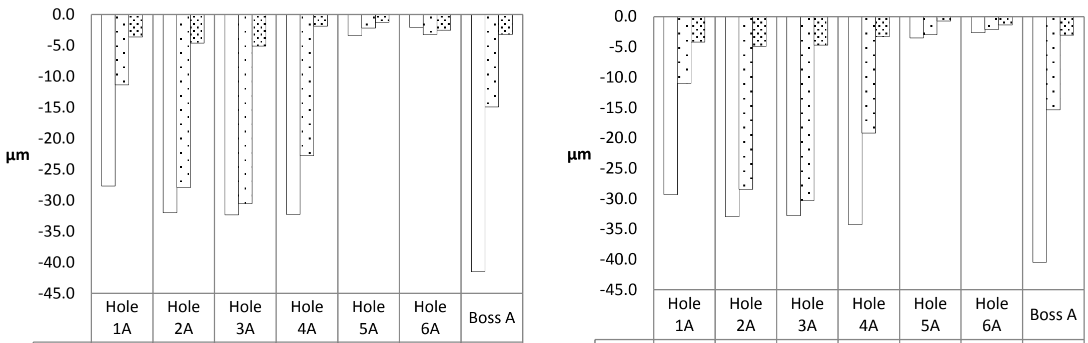
Figure 6-7 Measured value delta, size, two CMMs, CTC 1.



	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	21.9	-5.3	14.7	13.9		-1.4	40.8
Med	2.6	26.1	-2.9	13.3		0.6	3.5
High	1.0	-0.4	-1.2	0.2		0.1	-0.4

	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	18.5	2.8	19.0	14.2		-0.7	39.6
Med	1.5	23.6	1.5	12.1		1.2	3.4
High	0.6	-0.1	-1.3	0.0		0.1	-0.3

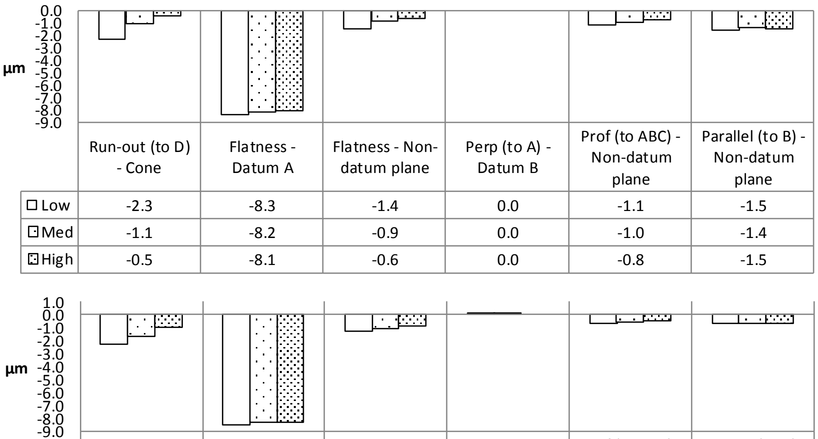
Figure 6-8 Measured value delta, position, two CMMs, CTC 1.



	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-27.7	-32.0	-32.3	-32.3	-3.4	-2.1	-41.5
Med	-11.4	-27.9	-30.5	-22.8	-2.2	-3.3	-14.9
High	-3.6	-4.6	-5.1	-1.9	-1.3	-2.5	-3.2

	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-29.3	-33.0	-32.8	-34.3	-3.5	-2.7	-40.5
Med	-11.0	-28.4	-30.3	-19.2	-3.0	-2.2	-15.4
High	-4.2	-4.9	-4.7	-3.3	-0.7	-1.4	-3.1

Figure 6-9 Measured value delta, cylindricity, two CMMs, CTC 1.



	Run-out (to D) - Cone	Flatness - Datum A	Flatness - Non-datum plane	Perp (to A) - Datum B	Prof (to ABC) - Non-datum plane	Parallel (to B) - Non-datum plane
Low	-2.3	-8.3	-1.4	0.0	-1.1	-1.5
Med	-1.1	-8.2	-0.9	0.0	-1.0	-1.4
High	-0.5	-8.1	-0.6	0.0	-0.8	-1.5

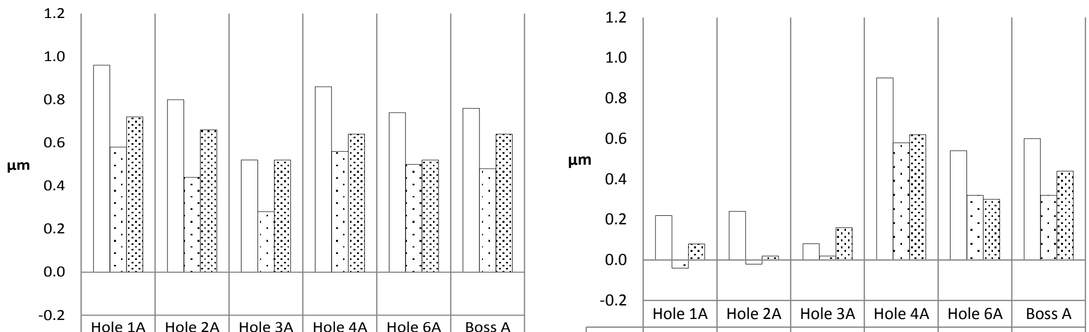
	Run-out (to D) - Cone	Flatness - Datum A	Flatness - Non-datum plane	Perp (to A) - Datum B	Prof (to ABC) - Non-datum plane	Parallel (to B) - Non-datum plane
Low	-2.3	-8.5	-1.3	0.0	-0.7	-0.7
Med	-1.6	-8.3	-1.0	0.0	-0.6	-0.6
High	-1.0	-8.3	-0.9	0.0	-0.4	-0.7

Figure 6-10 Measured value delta, other PMI (fixed datum), two CMMs, CTC 1.

6.5.3 Impact of varying sampling method level on datum features

The results from varying sampling method level on datum features, whilst holding the method fixed on the tolerance-controlled features, are summarised in Figure 6-11 to Figure 6-16; the source data is listed in Table B-6 to Table B-9. In an attempt to exaggerate the impact, the datum system was adjusted for Figure 6-12 to Figure 6-15 such that Datum C was moved away from the 'perfect' Hole 5A to the holes which have deliberate form.

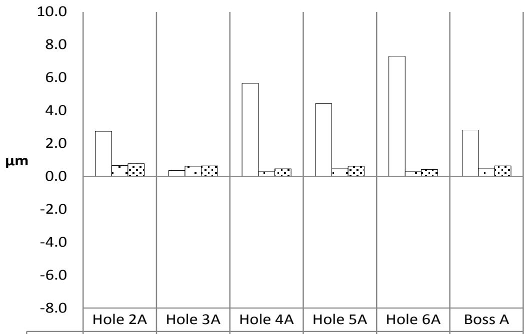
Similar to the observations made in Section 6.5.2, it can be seen that method levels can have a significant impact, and that trends are similar on both CMMs. However, the magnitude of the differences appears to be less pronounced, particularly when one considers that good practice would suggest that one should select datum features that have been produced with relatively little form error.



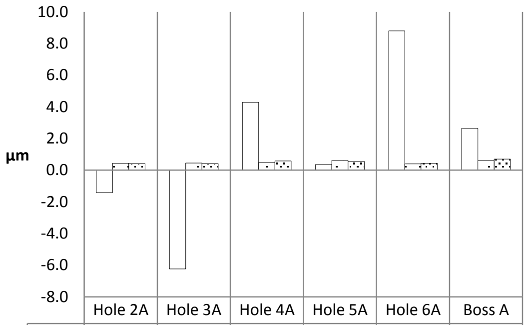
	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 6A	Boss A
Low	1.0	0.8	0.5	0.9	0.7	0.8
Med	0.6	0.4	0.3	0.6	0.5	0.5
High	0.7	0.7	0.5	0.6	0.5	0.6

	Hole 1A	Hole 2A	Hole 3A	Hole 4A	Hole 6A	Boss A
Low	0.2	0.2	0.1	0.9	0.5	0.6
Med	0.0	0.0	0.0	0.6	0.3	0.3
High	0.1	0.0	0.2	0.6	0.3	0.4

Figure 6-11 Measured value delta, position (datum on 5A), two CMMs, CTC 1.

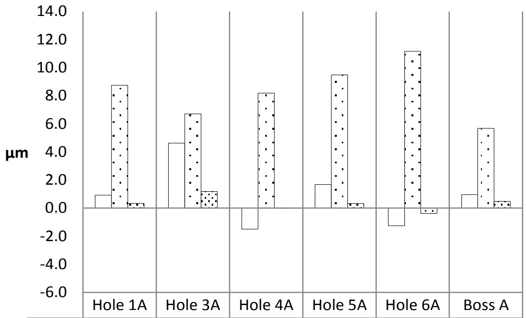


	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	2.7	0.4	5.7	4.4	7.3	2.8
Med	0.7	0.6	0.3	0.5	0.3	0.5
High	0.8	0.6	0.5	0.6	0.4	0.6

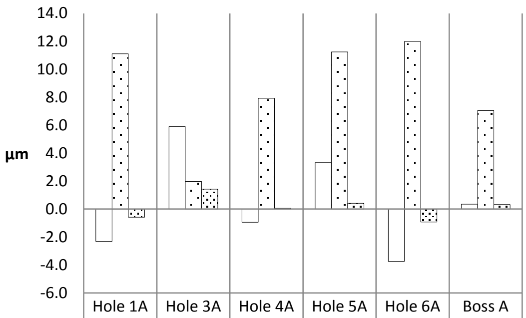


	Hole 2A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-1.4	-6.2	4.3	0.4	8.8	2.6
Med	0.4	0.5	0.5	0.6	0.4	0.6
High	0.4	0.4	0.6	0.6	0.4	0.7

Figure 6-12 Measured value delta, position (datum on 1A), two CMMs, CTC 1.

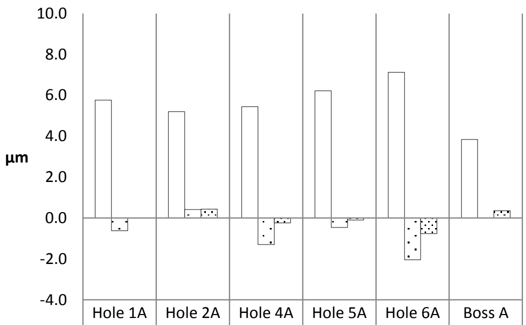


	Hole 1A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	0.9	4.6	-1.5	1.7	-1.3	1.0
Med	8.7	6.7	8.2	9.5	11.2	5.7
High	0.3	1.2	0.0	0.3	-0.4	0.5

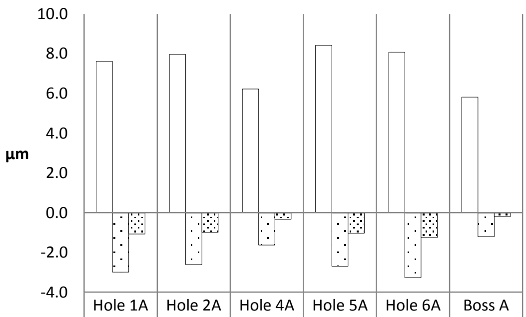


	Hole 1A	Hole 3A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	-2.3	5.9	-0.9	3.3	-3.7	0.3
Med	11.1	2.0	7.9	11.2	12.0	7.0
High	-0.6	1.4	0.1	0.4	-0.9	0.3

Figure 6-13 Measured value delta, position (datum on 2A), two CMMs, CTC 1.

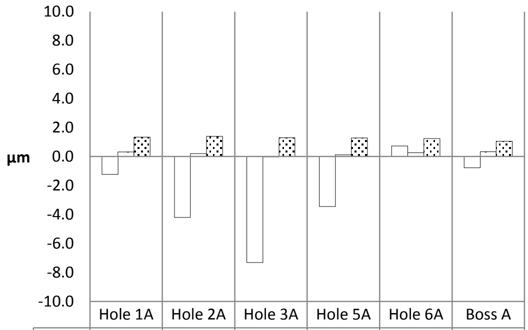


	Hole 1A	Hole 2A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	5.8	5.2	5.4	6.2	7.1	3.8
Med	-0.6	0.4	-1.3	-0.5	-2.0	0.0
High	0.0	0.4	-0.2	-0.1	-0.8	0.4

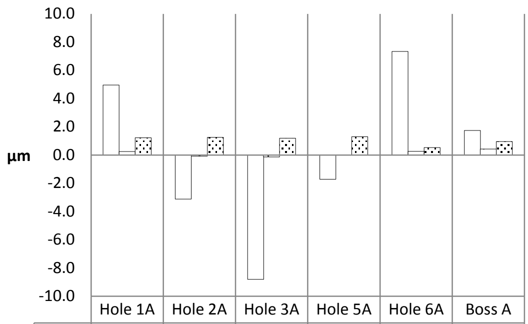


	Hole 1A	Hole 2A	Hole 4A	Hole 5A	Hole 6A	Boss A
Low	7.6	8.0	6.2	8.4	8.1	5.8
Med	-3.0	-2.6	-1.6	-2.7	-3.3	-1.2
High	-1.1	-1.0	-0.3	-1.0	-1.2	-0.2

Figure 6-14 Measured value delta, position (datum on 3A), two CMMs, CTC 1.

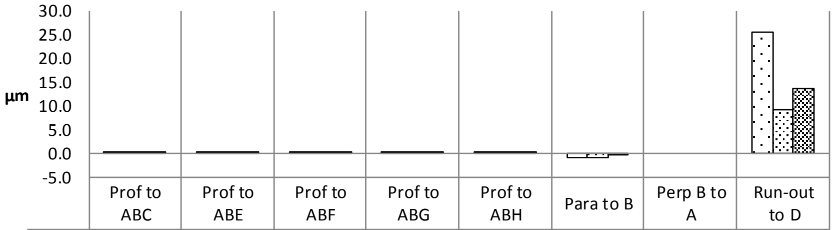


	Hole 1A	Hole 2A	Hole 3A	Hole 5A	Hole 6A	Boss A
Low	-1.2	-4.2	-7.3	-3.5	0.7	-0.8
Med	0.3	0.2	0.0	0.1	0.3	0.3
High	1.3	1.4	1.3	1.3	1.2	1.1

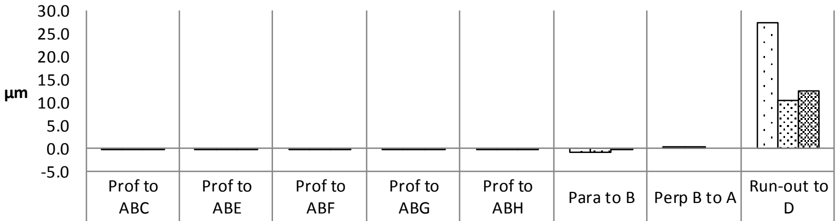


	Hole 1A	Hole 2A	Hole 3A	Hole 5A	Hole 6A	Boss A
Low	5.0	-3.1	-8.8	-1.7	7.3	1.7
Med	0.2	-0.1	-0.1	0.0	0.3	0.4
High	1.2	1.2	1.2	1.3	0.5	0.9

Figure 6-15 Measured value delta, position (datum on 4A), two CMMs, CTC 1.



	Prof to ABC	Prof to ABE	Prof to ABF	Prof to ABG	Prof to ABH	Para to B	Perp B to A	Run-out to D
Low	0.3	0.3	0.3	0.3	0.3	-1.1	0.0	25.4
Med	0.2	0.2	0.2	0.2	0.2	-1.0	0.0	9.0
High	0.3	0.3	0.3	0.3	0.3	-0.4	0.0	13.5



	Prof to ABC	Prof to ABE	Prof to ABF	Prof to ABG	Prof to ABH	Para to B	Perp B to A	Run-out to D
Low	-0.3	-0.3	-0.3	-0.3	-0.3	-1.1	0.0	27.1
Med	-0.2	-0.2	-0.2	-0.2	-0.2	-1.0	0.0	10.3
High	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	0.0	12.4

Figure 6-16 Measured value delta, other PMI (varied datum), two CMMs, CTC 1.

Of particular note is Figure 6-11 when compared to Figure 6-8. Both of these graphs show the impact of measured position using the same datum structure. It can be seen that the difference between the method levels is no more than 1 µm when strategy is varied on the datum features, though up to a 40 µm difference is found when varying the method on the tolerance-controlled features. It is likely that this is because all the datum features in this case have minimal form error.

6.5.4 Emergent finding on the importance of fitting algorithms

In order to increase confidence in the results, an additional step was taken to compare the tolerance assessments made when the same data set was run through different results analysis software (Table B-10 and Table B-11). Small differences were found for some of the measurands, though one can never know which one is 'right'. When reviewing these results with stakeholders, it was observed that default settings sometimes change between versions, and users may not always appreciate the importance of the algorithms. For example, software may default to a Gaussian fit for cylindricity, even though it can be inferred from both the ASME and ISO geometric dimensioning and tolerancing standards that Chebyshev would be a better choice. Even when programmers know which algorithms should be selected, they may not notice an incorrect default setting, or a change between software versions. Thus, the fitting algorithm should be included in a measurement standard, and it was resolved to make sure that this was modelled correctly in the subsequent experiments with UES.

6.5.5 Reflections on impact assessment

The results from varying method level, on both tolerance-controlled features and datum features, clearly show the impact that method levels can have when there is significant form error. Even when form error is less significant, an effect is discernible for certain measurands, such as run-out on the cone (Figure 6-10 and Figure 6-16).

Therefore, it can be concluded that, at least for these particular measurands, in this particular context, method levels can have a significant and reproducible impact on measurement error. Accordingly, it now appears feasible to build on this finding and determine whether simulation can be used to select a method level according to a target uncertainty, as outlined in the template selection sequence diagram (Figure 6-5).

6.6 Integrity appraisal of proposed measurement standard system

After establishing that different sampling methods can lead to significantly different results through the experiments reported in Section 6.5, the reliability of uncertainty statements now needs to be considered.

Uncertainty evaluation is at the heart of the proposed measurement standard system, and simulation needs to be accurate and robust for UES to be used in the development of measurement standards. The question can be considered in terms of integrity for uncertainty management, for which measures were developed in Section 6.3.3.

6.6.1 Experimental design for uncertainty simulation

The key inputs required for UES are:

- Measuring system characteristics, which includes performance measures for the CMM and probe system, as well as information about the environment;
- Measurement plan, which includes PMI, the sampling strategy, and fitting algorithms;
- Manufacturing signature – in other words, the form error of all relevant features.

The output will be a prediction of the measurement uncertainty for each measuring task – this will be called a 'simulated uncertainty'.

A schematic showing the UES, with its inputs and outputs, is shown in Figure 6-17.

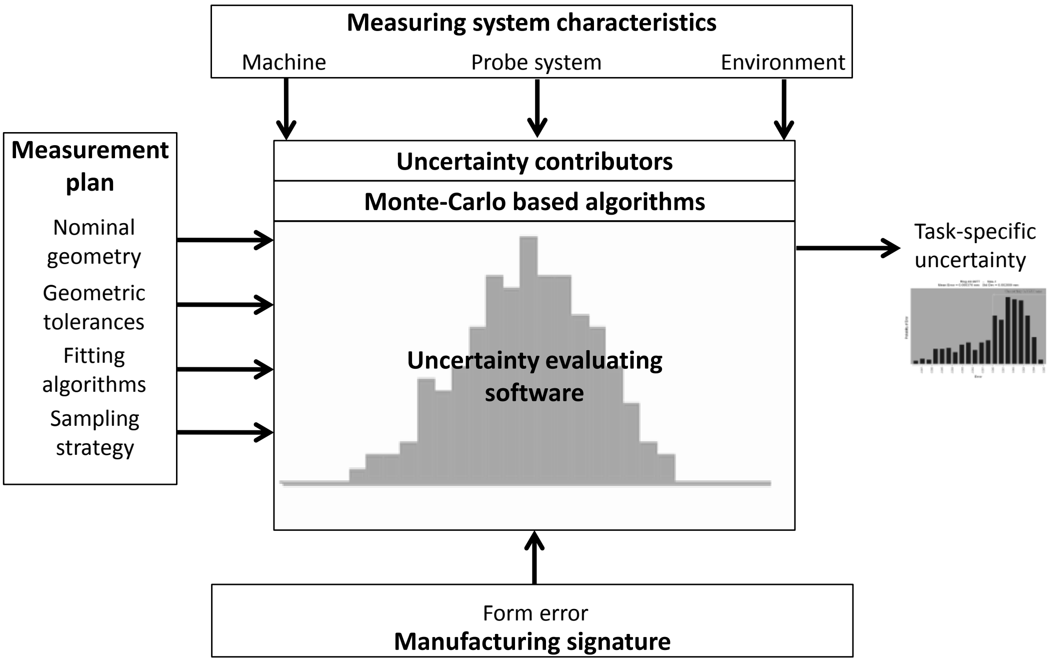


Figure 6-17 Inputs for UES.

Measuring system characteristics were captured using data from ISO 10360-2 (2009) performance tests.

Measurement plan data was input in two stages. Firstly the nominal geometry and PMI were input based on information contained in the master engineering model which would be stored within PLM. Secondly the sampling points and fitting algorithms were input based on the CMM measurement program.

The manufacturing signature was captured through a mixture of scanning (for holes) and a dense number of points (for planes). The measured points were input into the UES, as shown in Figure 6-18. Where the visualisation within the UES suggested that there might be an error, this was examined further and any obvious outliers removed – for example as shown in Figure 6-19. Finally, the sampling pattern (nominal measurement points) which was generated for the measurement program was imported into the UES, as shown in Figure 6-20. Two hundred and fifty runs were performed in each case.

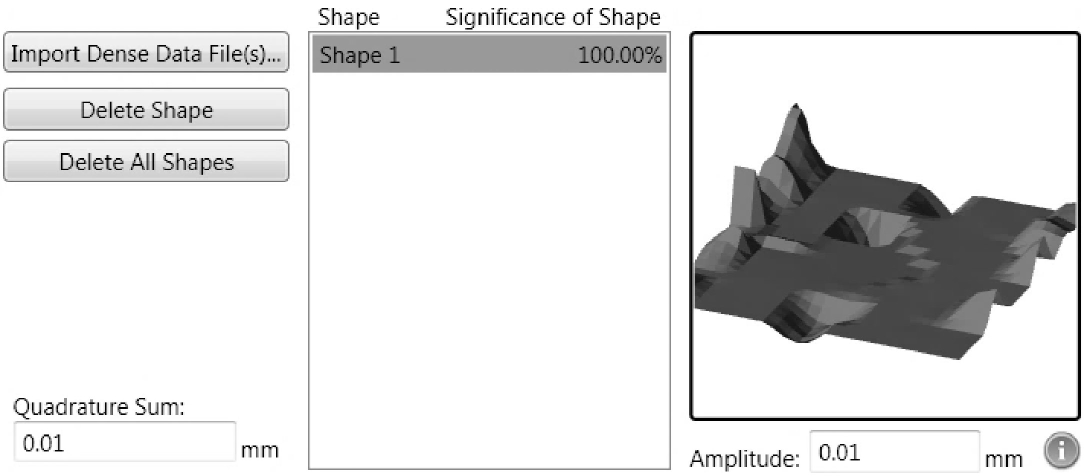


Figure 6-18 Result of importing form error to Pundit/CMM®, CTC 1.

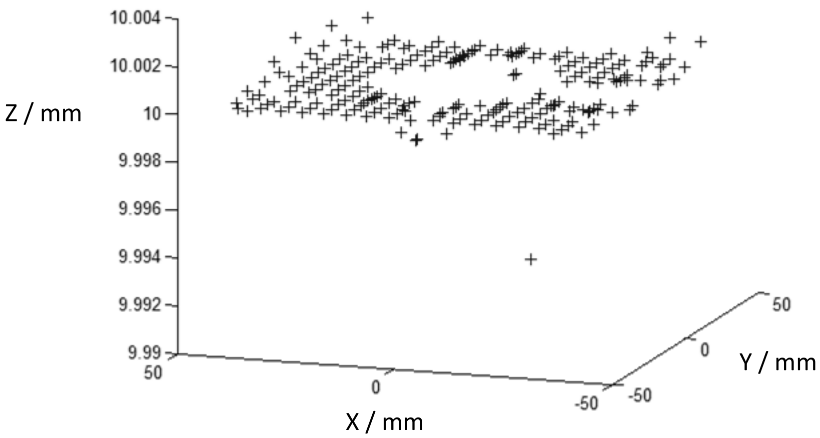


Figure 6-19 Form error for datum A, showing an outlier, CTC 1.[2]

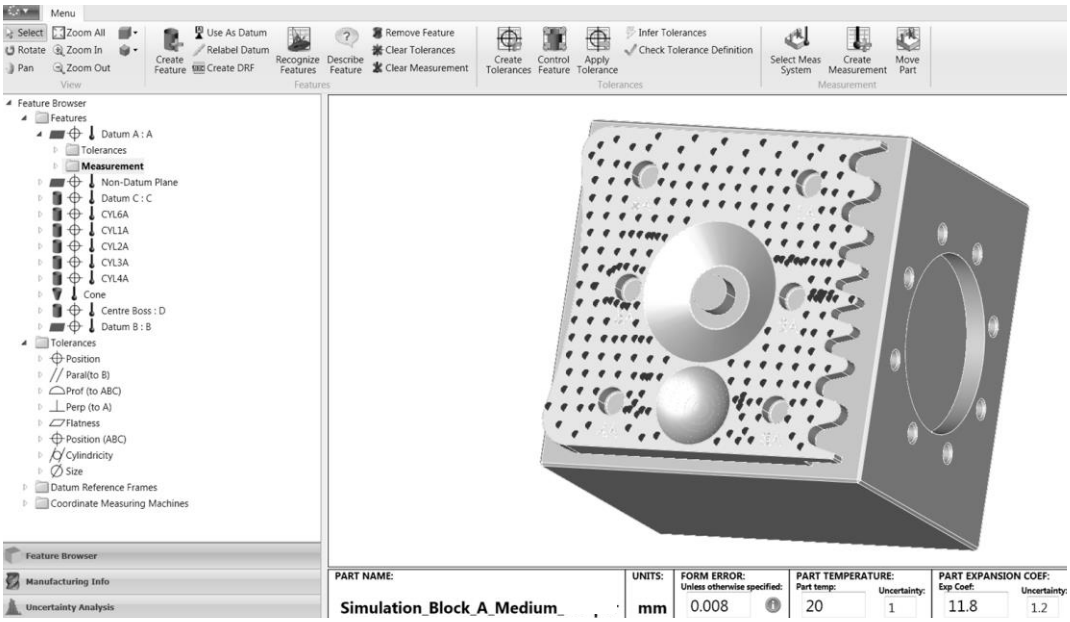


Figure 6-20 Screenshot of Pundit/CMM®, sampling strategy on Datum A, CTC 1.

6.6.2 Impact of varying sampling method level on uncertainty simulation

The simulation was performed for the first scenario (Section 6.5.2), in which sampling method level was varied on the tolerance-controlled features but fixed for the datum features, since this is where the biggest impact had been found.

Examples of the results from the simulations are shown in Figure 6-21 to Figure 6-24; the full set of results is shown in Figure B-1 to Figure B-4. In each case, the simulation was performed for CMM A, CMM B, and a ‘perfect’ CMM system. The perfect CMM system was modelled as one in which the CMM hardware, probing system, and environment, did not introduce any measurement error. It can be seen that in every case, there is a trend of decreasing simulated uncertainty with higher method levels. The magnitude and rate by which simulated uncertainty decreases depends on the PMI type and, in the case of hole position, the CMM system.

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[2] This graph was created by Dr. Jon Baldwin, Metrosage in advance of carrying out a form error computation.

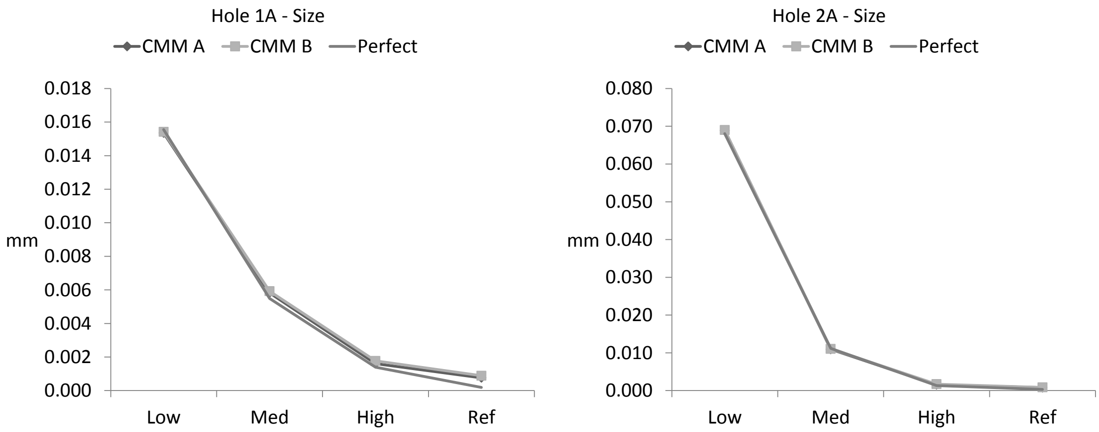


Figure 6-21 $U_{\text{sim,}}$ size, Hole 1A (left) and Hole 2A (right), CTC 1.

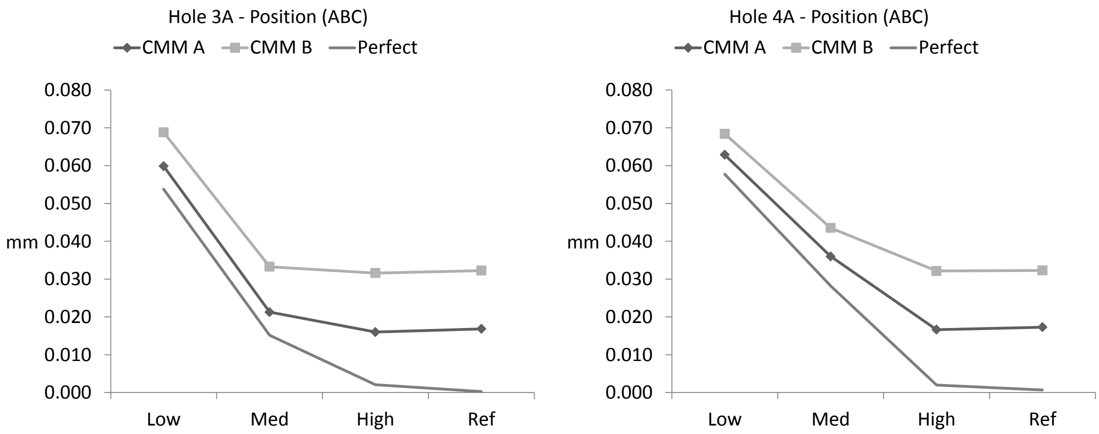


Figure 6-22 $U_{\text{sim,}}$ position, Hole 3A (left) and Hole 4A (right), CTC 1.

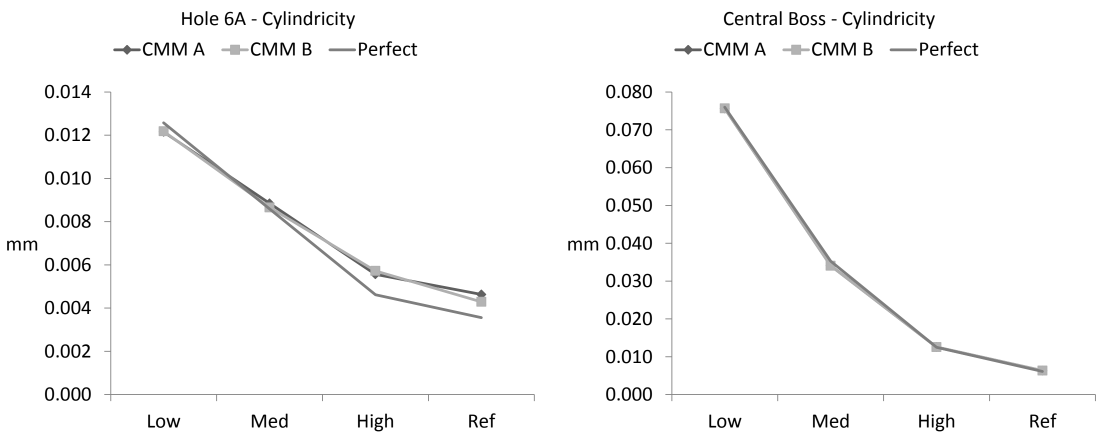


Figure 6-23 U_{sim}, cylindricity, Hole 6A (left) and Boss (right), CTC 1.

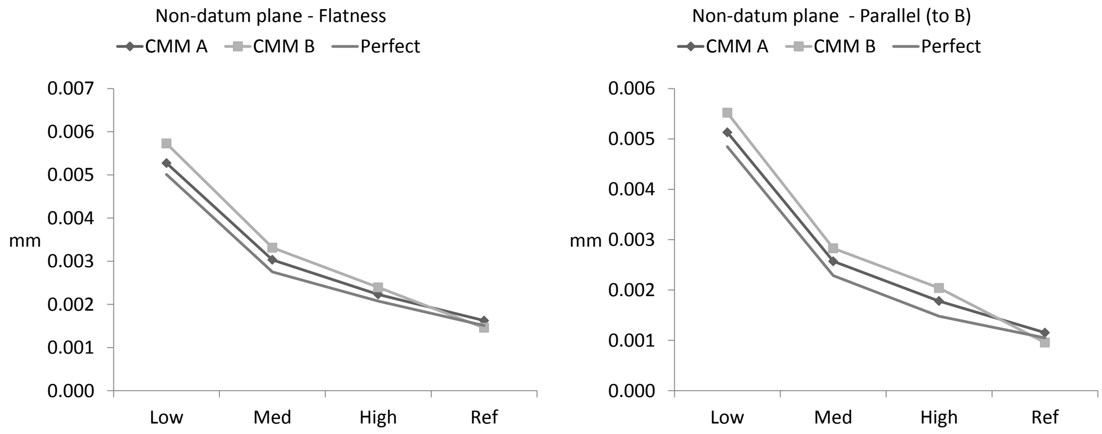


Figure 6-24 U_{sim}, flatness (left) and parallelism (right), CTC 1.

6.6.3 Correlation of measured values with uncertainty simulation

The averaged measured results, as reported in Section 6.5.2, were also correlated with the simulation results and compared with results from calibration that had been performed at the National Physical Laboratory (Table B-12). Examples are shown in Figure 6-25 to Figure 6-28; the full set of results is shown in Figure B-5 to Figure B-11.

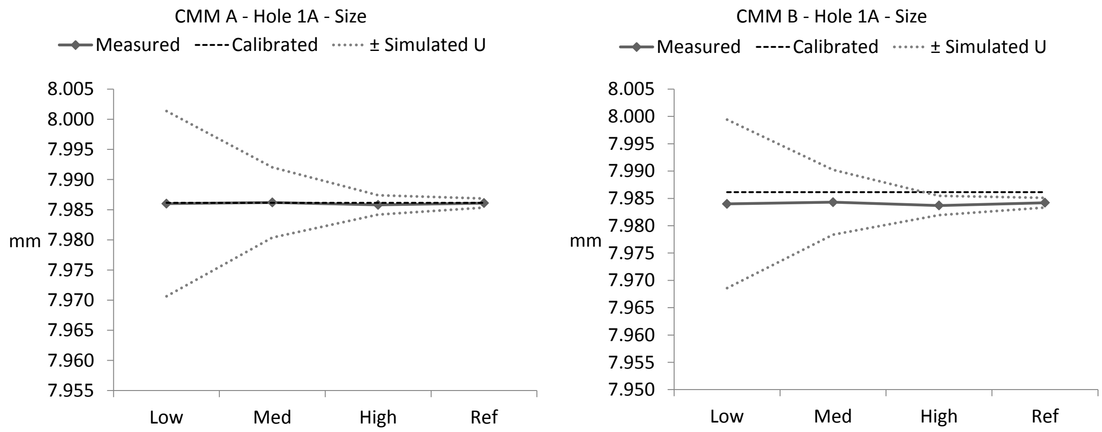


Figure 6-25 Measured value and U_{sim}, size, Hole 1A, two CMMs, CTC 1.

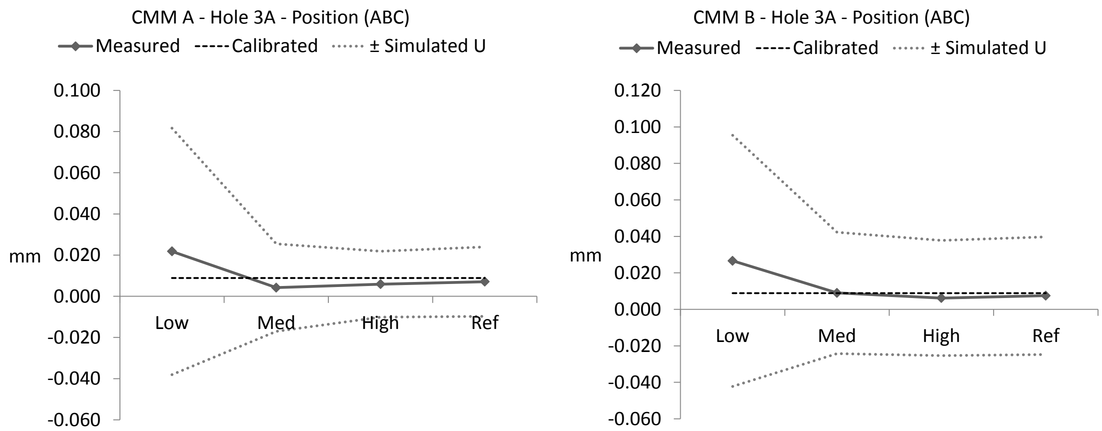


Figure 6-26 Measured value and U_{sim}, postion, Hole 3A, two CMMs, CTC 1.

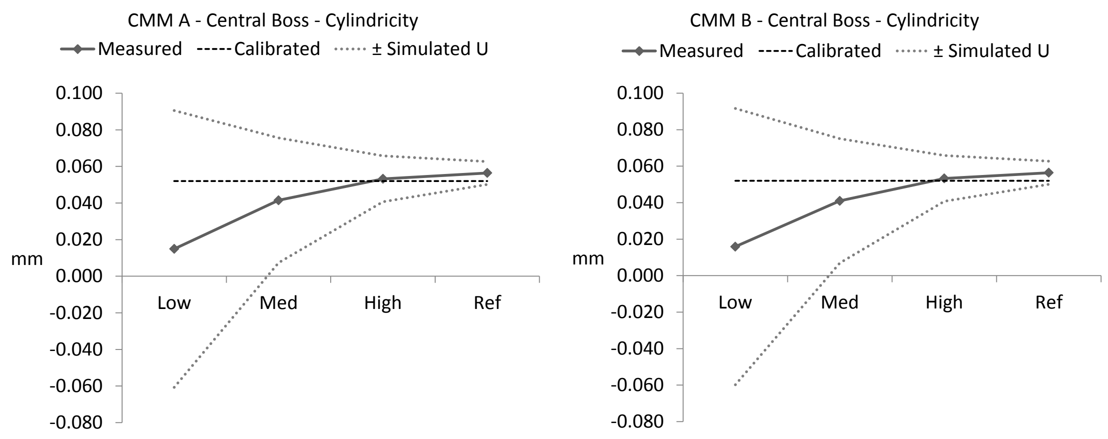


Figure 6-27 Measured value and U_{sim}, cylindricity, Boss A, two CMMs, CTC 1.

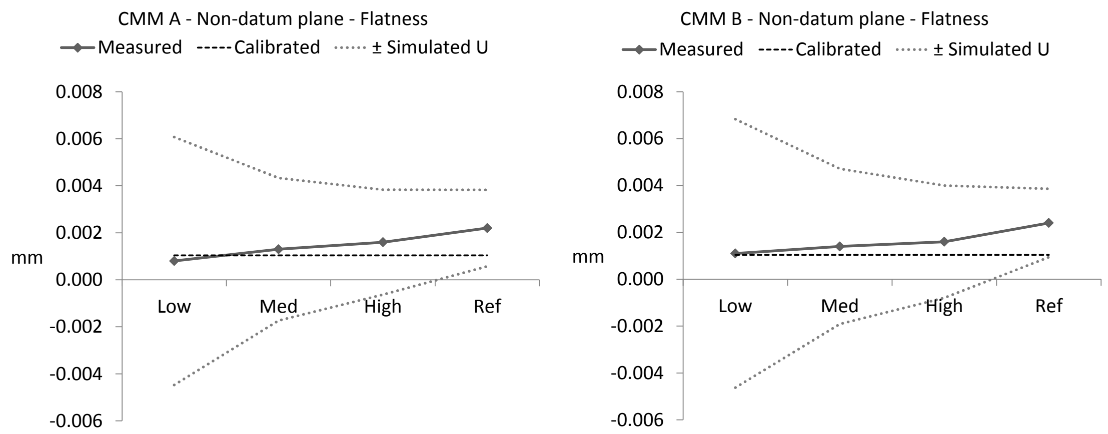


Figure 6-28 Measured value and U_{sim}, flatness, plane, two CMMs, CTC 1.

In most cases, the measured values coupled with simulated uncertainty take in the calibrated value (as per equations [6-1] and [6-2]), which reinforces the view that UES provides actionable results.

$$\text{Measured value} + U_{\text{sim}} > \text{Calibrated value} + U_{\text{cal}} \qquad [6\text{-}1]$$

$$\text{Measured value - } U_{\text{sim}} < \text{Calibrated value - } U_{\text{cal}} \qquad [6\text{-}2]$$

There are exceptions. For example, the high and reference method levels appear to under-report the size of Hole 1A on CMM B as compared to the calibration (Figure 6-25). However, the differences are in the order of 1 µm and could partly be explained by the uncertainty in calibration which is not available, and is therefore not included on the charts. The reference strategy for many of the form tolerances also appears to over-report deviations from nominal as compared to calibration in many cases, though still satisfies the criteria in equations [6-1] and [6-2]. This latter result may be due to the fact that the reference method actually used more points than were used during calibration, thus potentially hitting more high spots.

It may also be observed that in many cases there is a relatively small difference in the magnitude of measured values for each method level as compared with the change in simulated uncertainty. This may be due to the fact that the physical measurements did not cover as full a range of variation as included in the simulation. For example, temperature may have been more constant than described for simulation. Additionally, the measured values reported are an average after five runs, whilst the simulation assumed just one run. Moreover, the UES was run in simulation-by-constraints mode meaning that errors from *any* CMM that could meet the performance specification were included in the simulation.

6.6.4 Reflections on integrity appraisal

The proposed approach for using UES within a measurement standard system can be appraised using the measures of integrity for uncertainty management outlined in Section 6.3.3; that is, how complete, how rigorous, and how apposite was the uncertainty management process when applied to this test case?

- Completeness

  For completeness, the measurement uncertainty associated with all of the PMI on the model should be managed. In this study, only the sampling method and CMM system were varied. The trends when varying method levels between CMMs were very similar in all cases. Twenty-six measurands were studied, from which there were five instances where the method level appeared to have little impact: Size and cylindricity of Hole 5A; position of Hole 6A; flatness of Datum A, and; perpendicularity of Datum B. This can be confirmed visually through reviewing the graphs in Figure B-1 to Figure B-4, where these five instances are highlighted. There were also two measurands for which simulation proved difficult: Run-out of the cone, and profile of the non-datum plane. Thus, the uncertainty of nineteen of the measurands on CTC 1 could be regarded as 'manageable' through varying method level simply by adjusting the sampling method level; the completeness score for uncertainty management of CTC 1 is 73 % (19 out of 26), using sampling method alone.

- Rigour

  For rigour, there are two tests to be passed. Firstly, one needs to be satisfied that the simulated uncertainty is valid. Secondly, it is necessary to ensure that the most significant uncertainty contributors are included in the analysis. Since calibrated values were available for many of the PMI types, the two tests were combined by checking whether the measured value with its associated uncertainty took in the calibrated values and the associated uncertainty of the calibration (as per equations [6-1] and [6-2] in Section 6.6.3). In most instances, the check was passed, though with some exceptions. This highlights the danger of a fully automated solution; an expert should still be involved to make judgements as to whether the simulated results appear reasonable before acting on them. Overall though, the results were encouraging, and 91 % (42 out of 46) measurands passed the check for all four strategies.

  Note: The instances which failed are highlighted in Figure B-5 to Figure B-11; the two measurands where simulation proved difficult to achieve, and one measurand for which there was no calibration data available, are excluded from the analysis. Marginal results, such as those discussed in Section 6.6.3 were assessed as a pass.

- Appositeness

  For appositeness, a method for calculating uncertainty is sought that strikes a balance between rigour and cost. For example, in this study the measuring system was characterised using existing data from an ISO 10360-2 (2009) test, rather than a full parametric model, because it was felt that the cost of acquiring the necessary data to more completely model the CMM would be greater than the benefit this would bring. If the resultant sampling methods were found to be too costly to implement, or no strategy could be found to meet the target uncertainty, this decision could be reviewed.

In short, it has been shown that the system outlined in the template selection sequence diagram (Figure 6-5) can successfully be applied as an aid to CMM measurement planning, at least as far as the 'decision matrix'. In the next section, a demonstration will be developed in an attempt to validate the proposed system.

6.7 Demonstration of system to develop measurement standards

Having shown that different sampling methods can lead to significantly different results, and that reliable uncertainty statements can be created through UES, a demonstration system was built in order to run the whole template selection process (Figure 6-5). Two CTCs were put through the system. The first was run on a series of nominally identical test blocks which were known to have been manufactured with a range of 'real' dimensions. The second CTC was designed to represent a small production run.

6.7.1 System demonstration for components that vary piece-to-piece

The process thus far could be criticised because it has only been run once. In addition, the Rolls-Royce multi-feature artefact could be regarded as overly simple with its shallow '2.5D' features, thus limiting the type of studies that can be performed. For these reasons, the demonstration was developed around a different component which was designed and manufactured by Aero Engine Controls. This component has more depth, and is illustrated in Figure 6-29.

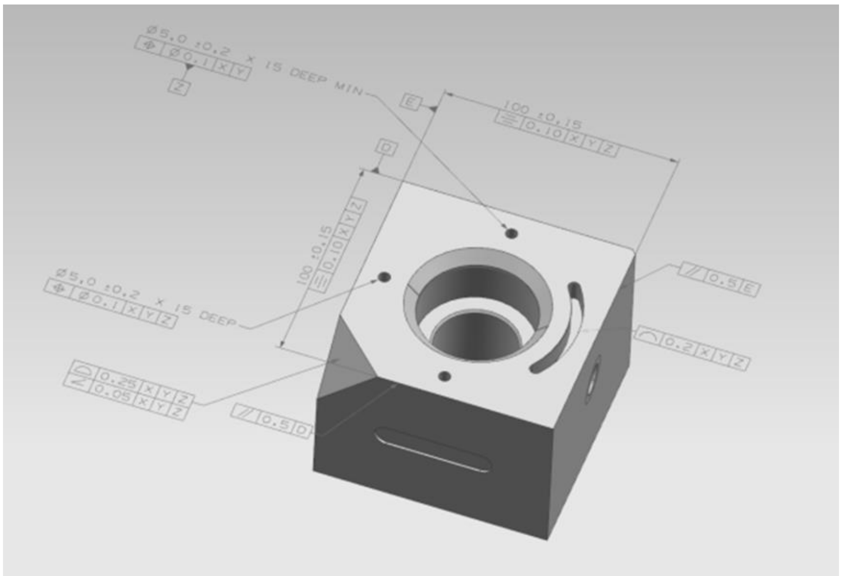


Figure 6-29 Aero Engine Controls test block with PMI, CTC 2.

The block is used by Aero Engine Controls to test the measurement capability of its own systems and that of its suppliers and contains PMI which is common within its business. Eight of these blocks were loaned, without revealing as to how they varied, though it was expected that there would be systematic variations in feature size. The eight blocks were measured using all four sampling method levels – designed to be similar to those used on CTC 1. The method levels are listed in Table 6-5, and were programmed using measurement templates in Siemens NX-CMM (Figure 6-30). The major difference, as compared with CTC 1, is that the low, medium, and high sampling strategies were not subsets of the reference strategy.

Table 6-5 Sampling method levels, CTC 2 and CTC 3.

Method level		Cylindrical feature			Planar feature
		Rows	Points / row	Distribution	Points (grid)
1	Low	2	4	Birdcage	U=2, V=3
5	Med	3	4	Birdcage	U=3, V=4
10	High	4	11	Staggered	U=4, V=5
10*	Ref	4	67	Staggered	U-16,V=16
	Scan	20	95	Latitudinal	200+

Note: For the Reference method level, 13 points were placed on each row of the small radii arc on the curved slot, whilst 67 points were placed on the large arcs

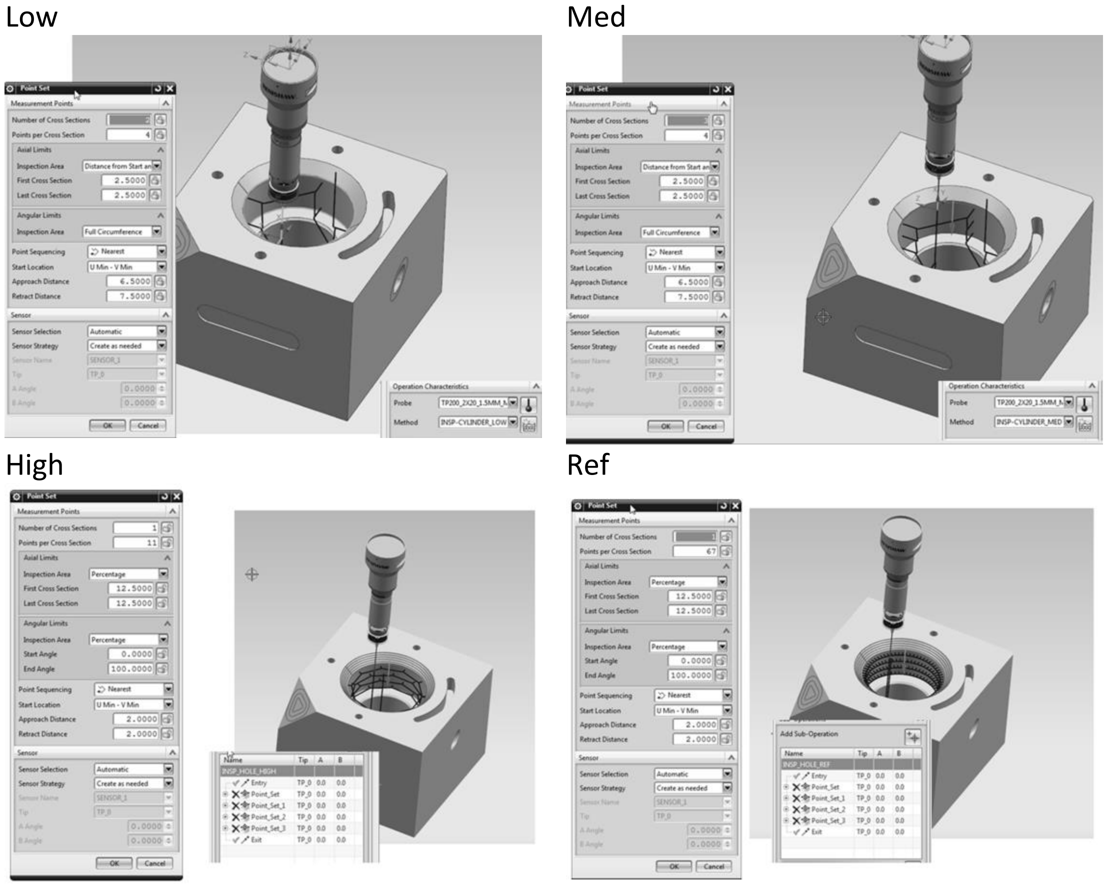


Figure 6-30 Measurement templates, as applied to a feature, CTC 2.[3]

[3] The PMI and sampling methods were input into Siemens NX-CMM by Roland Dixon, Siemens.

The CMM (CMM C, as described in Table 4-6) was equipped with a probing system which is capable of five-axis scanning, and this facility was used to capture form error, an overview of which is shown in Figure 6-31. Subsequent measurement was performed in discrete point mode. The program was run once for each of the eight blocks, and the laboratory was stabilised at 20 ^{o}C ± 1 ^{o}C.

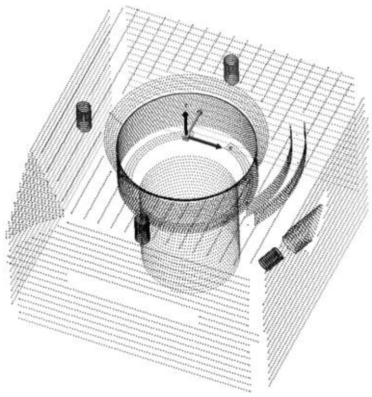


Figure 6-31 Scan points for capturing form error, CTC 2.

The measuring system characteristics, the measurement plan for each method level, and the form error data for each block were input into the UES. Thus the UES was run four times for each of the eight components, providing thirty-two simulated uncertainty values for each measurand. There were nineteen measurands to evaluate (Table B-13).

One of the blocks had previously been calibrated at the National Physical Laboratory[4], so this was used to check the integrity of the uncertainty management system, as was done for CTC 1 in Section 6.6.4:

- Completeness

  There were ten instances where the sampling method had no discernable impact, as highlighted in the graphs in Figure B-12 to Figure B-14. The completeness score for uncertainty management for CTC 2 is therefore 47 % (9 out of 19).

- Rigour

  By correlating the measured value and simulated uncertainty against the calibrated value for each measurand (where available), it was found that 61 % (11 out of 18) passed the tests (equations [1] and [2] in Section 6.6.3). However, on later analysis it was found that the measurement program was incorrect for two of the holes, one of which was used as a datum feature (Datum Y). The probe ball size was too small which led to the probe stem contacting the sides of the hole before the ball. Whilst limited to the high method for the datum, this affected all method levels on the 50 mm hole

[4] The block identity numbers for CTC 2 have been disguised for the purpose of reporting the results in this thesis. This is so that the blocks may continue to be used for their more normal purpose, as a reference set for evaluating measurement capability. For example, ‘block 8’ in this thesis does not refer to the physical block marked ‘8’.

(Figure 6-32). When these false results are discounted, the revised score for rigour is 88 % (15 out of 17).

- Appositeness

  Whilst only 47 % of the PMI *for this particular block* appear to be affected significantly by sampling method, the high rigour score was encouraging and considered to be sufficient for a worthwhile demonstration.

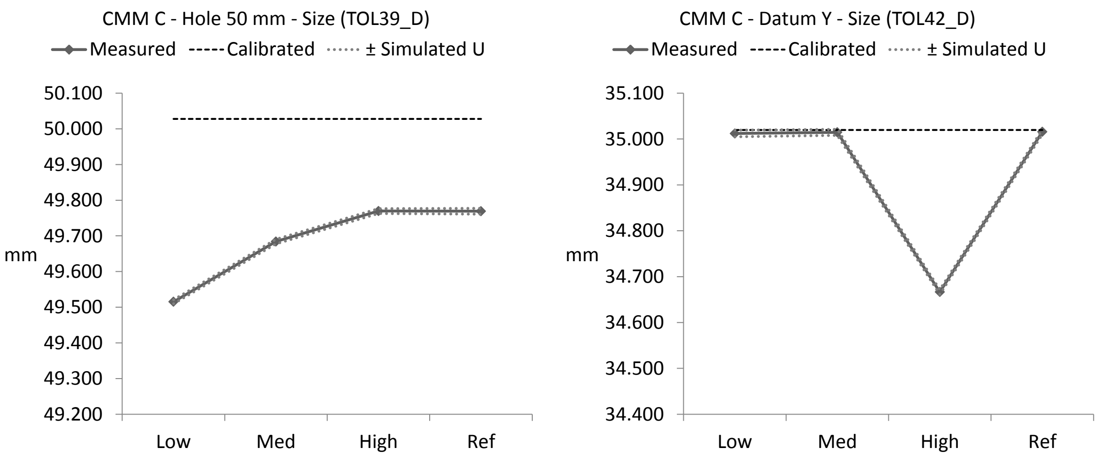


Figure 6-32 Measured value and U_{sim}, diameter, block 1, CTC 2.

The first stage of the demonstration involved simulating uncertainty through the UES on the remaining seven blocks. Two examples of the results from the UES are shown in Figure 6-33 and Figure 6-34. In both of these examples, it is hard to identify any patterns through simulation.

The fact that some lines cross indicate that the analysis cannot be extrapolated from one method level to others; the simulation must be performed with the actual method level under consideration.

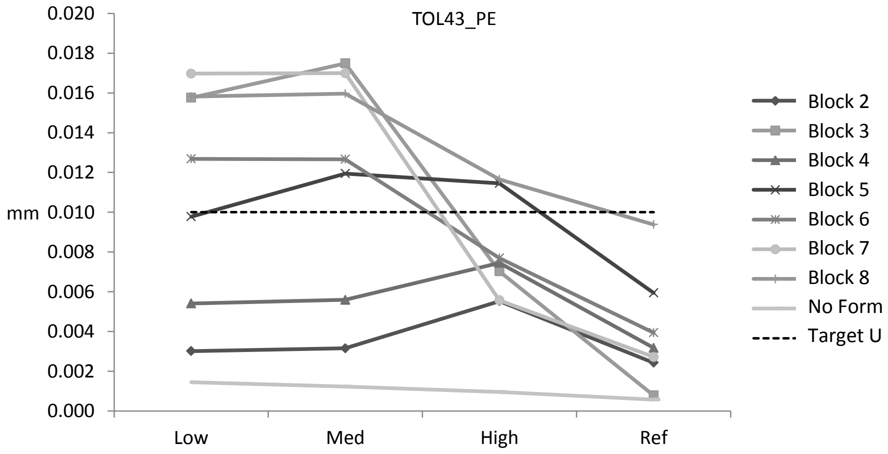


Figure 6-33 U_{sim} and U_T, perpendicularity of datum Y, CTC 2.

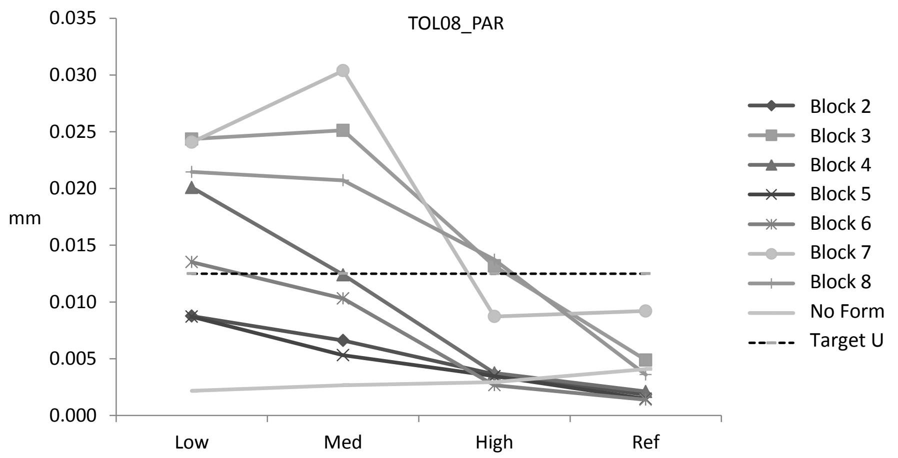


Figure 6-34 U_{sim} and U_T, parallelism of right face, CTC 2.

Following simulation, the blocks were measured on CMM C. The measured values were combined with simulated uncertainty for all measurands and on all blocks, providing a rich data set from which to check the consistency of simulated uncertainty between method levels. Two examples of the correlated data are shown in Figure 6-35, and an example of how the correlation differed between blocks is shown in Figure 6-36; Figure B-18 shows an example across all blocks.

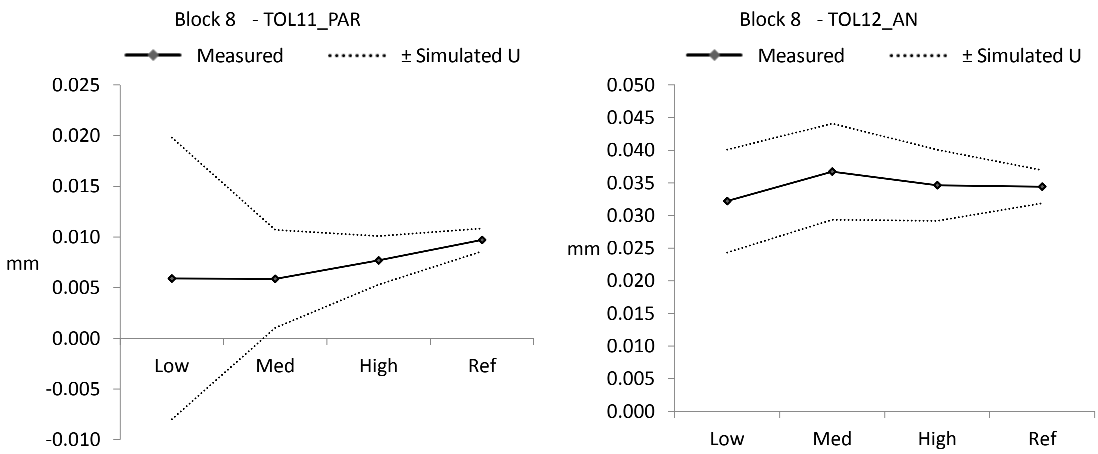


Figure 6-35 Measured value and U_{sim}, parallelism, angularity, block 8, CTC 2.

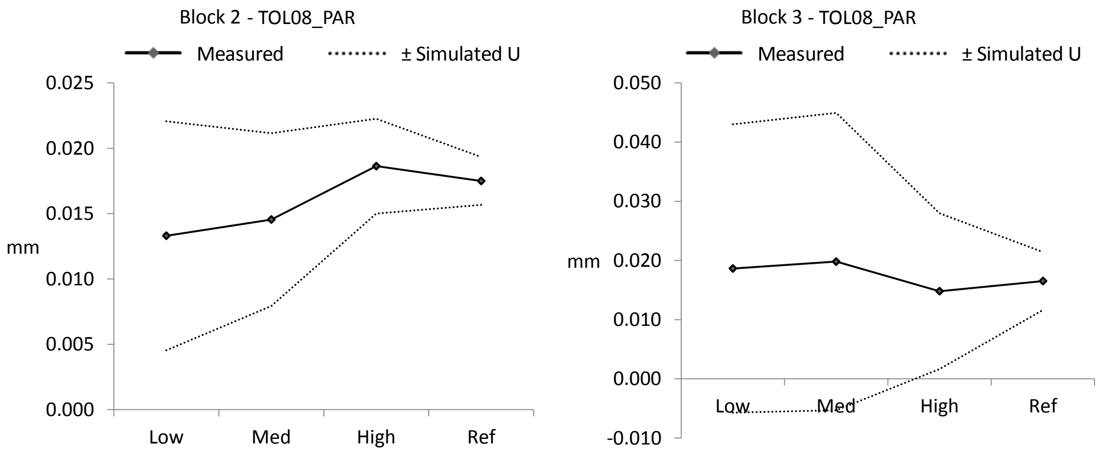


Figure 6-36 Measured value and U_{sim}, parallelism, blocks 2 and 3, CTC 2.

Next, the decision matrix discussed in Section 6.4.2 was prototyped using Microsoft Excel®, which was used as a surrogate for the PLM system. The full process is illustrated through the connecting arrows from Figure 6-37 to Figure 6-40; the shaded cells indicate the fields that need to be populated at each stage.

	Datum	Non-datum
Target U proportion	0.1	0.25

Feature name	Used for DRF construction?
CORNER_FACE	
CURVE_SLOT_FACE_01	
CURVE_SLOT_FACE_02	
DATUM_D : D	y
DATUM_E : E	y
DATUM_Y : Y	y

PMI type	Tolerance	Feature	*Is DRF?*	*Target U*
TOL06_DB	0.3	FACE_RIGHT	*0*	*0.075*
TOL08_PAR	0.05	FACE_RIGHT	*0*	*0.0125*
TOL10_PR	0.2	CURVE_SLOT_FACE_01	*0*	*0.05*
TOL10_PR	0.2	CURVE_SLOT_FACE_02	*0*	*0.05*
TOL11_PAR	0.05	FACE_FRONT	*0*	*0.0125*
TOL12_AN	0.05	CORNER_FACE	*0*	*0.0125*
TOL13_PR	0.25	CORNER_FACE	*0*	*0.0625*
TOL14_1_TP	0.1	HOLE_5MM_01	*0*	*0.025*
TOL14_2_TP	0.1	HOLE_5MM_02	*0*	*0.025*
TOL15_1_D	0.4	HOLE_5MM_01	*0*	*0.1*
TOL15_2_D	0.4	HOLE_5MM_02	*0*	*0.1*

Figure 6-37 Determining a target uncertainty per PMI, CTC 2.

PMI type	*Feature*	*Target U*	1 Low	5 Med	10 High	10* Ref	*Method*	*Ue*	*Ue/Ut*	*Trend*	*Ref/Low*
TOL06_DB	FACE_RIGHT	0.075	0.005586	0.004971	0.004571	0.004603	1 Low	0.0056	0.07		0.8
TOL08_PAR	FACE_RIGHT	0.0125	0.00876	0.006611	0.003629	0.001827	1 Low	0.0088	0.70		0.2
TOL10_PR	CURVE_SLOT_FACE_01	0.05	0.022142	0.020726	0.020942	0.021836	1 Low	0.0221	0.44		1.0
TOL10_PR	CURVE_SLOT_FACE_02	0.05	0.020497	0.020624	0.020749	0.02181	1 Low	0.0205	0.41		1.1
TOL11_PAR	FACE_FRONT	0.0125	0.008936	0.003458	0.002072	0.001035	1 Low	0.0089	0.71		0.1
TOL12_AN	CORNER_FACE	0.0125	0.007582	0.008729	0.004597	0.002778	1 Low	0.0076	0.61		0.4
TOL13_PR	CORNER_FACE	0.0625	0.026438	0.023413	0.02592	0.026575	1 Low	0.0264	0.42		1.0
TOL14_1_TP	HOLE_5MM_01	0.025	0.071717	0.070921	0.069451	0.069326	Review	0.0693	2.77		1.0
TOL14_2_TP	HOLE_5MM_02	0.025	0.073708	0.072046	0.066704	0.066306	Review	0.0663	2.65		0.9
TOL15_1_D	HOLE_5MM_01	0.1	0.009186	0.00718	0.005589	0.005568	1 Low	0.0092	0.09		0.6
TOL15_2_D	HOLE_5MM_02	0.1	0.009119	0.007312	0.003941	0.004371	1 Low	0.0091	0.09		0.5
TOL16_DB	FACE_FRONT	0.075	0.011933	0.008722	0.007012	0.006196	1 Low	0.0119	0.16		0.5
TOL18_TP	DATUM_Z : Z	0.01	0.076316	0.076206	0.071637	0.070733	5 Rev	0.0707	7.07		0.9

Figure 6-38 Deriving the most apposite method level (for block 2), CTC 2.

Block ID
1
2
3
4
5
6
7

Feature	*1 Low*	*5 Med*	*10 High*	*10* Ref*	*Review*	*Highest*
CORNER_FACE	2					1
CURVE_SLOT_FACE_01	1					1
CURVE_SLOT_FACE_02	1					1
DATUM_Y : Y	1		1			10
DATUM_Z : Z	1				1	Review
FACE_FRONT	2					1
FACE_RIGHT	2					1
HOLE_50MM			1	1	2	Review
HOLE_50MM_DEPTH					1	Review

Figure 6-39 Decision matrix (for block 2), CTC 2.

Feature	PMI type	PMI ID	RigourName	Target U	Ue
DATUM_Z : Z	**TOL18_TP**	4-1	**5 Rev**	0.01	0.0707
	TOL19_D	4-2	**1 Low**	0.04	0.0098

Figure 6-40 Mapping back from features to PMI for further analysis, CTC 2.

Firstly, a target uncertainty was set for each PMI. For the purpose of the demonstration, the target was set to be a proportion of the tolerance value, and was set higher for features that are used within datum reference frames (DRF) (Figure 6-37). A simple ratio was applied for the demonstration, though one could envisage adjusting the target uncertainty according to mathematical rules, such as those proposed by Forbes et al. (2013) in a study which happened to be based on the Rolls-Royce multi-feature artefact (CTC 1).

Secondly, simulated uncertainty was associated to each PMI, allowing a calculation to be made to find the lowest method level that could be used to meet the target uncertainty (Figure 6-38).

Thirdly, using this data, the decision matrix was formed from which the 'commodity-based measurement standard' could be formed (Figure 6-39).

Fourthly, if necessary, the data could be interrogated further to identify the source of any features that may be deemed as requiring review when the target uncertainty cannot be met for one or more of the related PMI (Figure 6-40).

Finally, graphs such as those shown in Figure 6-41 (more examples are shown in Figure B-19 to Figure B-21) were generated in order to allow the impact of method level on simulated uncertainty to be visualised, and the integrity of the measurement planning process to be reviewed

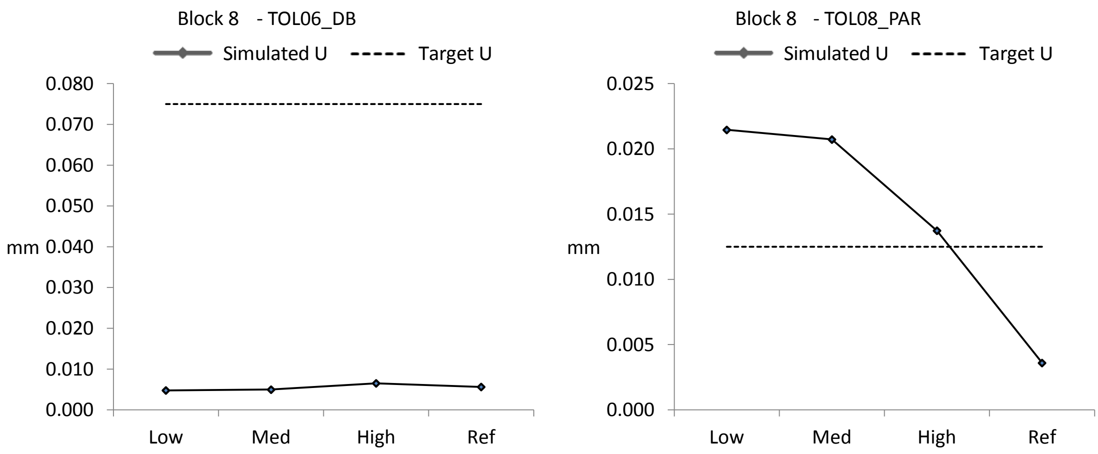


Figure 6-41 U_{sim} and U_T, linear distance and parallelism, block 8, CTC 2.

6.7.2 System demonstration for components that vary batch-to-batch

In the previous section, the foundations for a full demonstration were created through piloting the system eight times on components with unknown manufacturing signatures. In this section, the demonstration is run on three series of similar components, with the intent of mimicking a batch production run.

For this second demonstration, an artefact developed by NIST was employed. This artefact is one of five which has been created in order to test PMI interoperability between CAD systems and across different exchange formats (Frechette et al., 2013).

The first of the five models is shown in Figure 6-42, and has been employed as CTC 3. Full details of the model can be found at (NIST, 2014). This artefact is of particular interest because it is designed to contain the most common PMI types in general industrial use, as validated by PMI and CAD experts (Frechette et al., 2013).

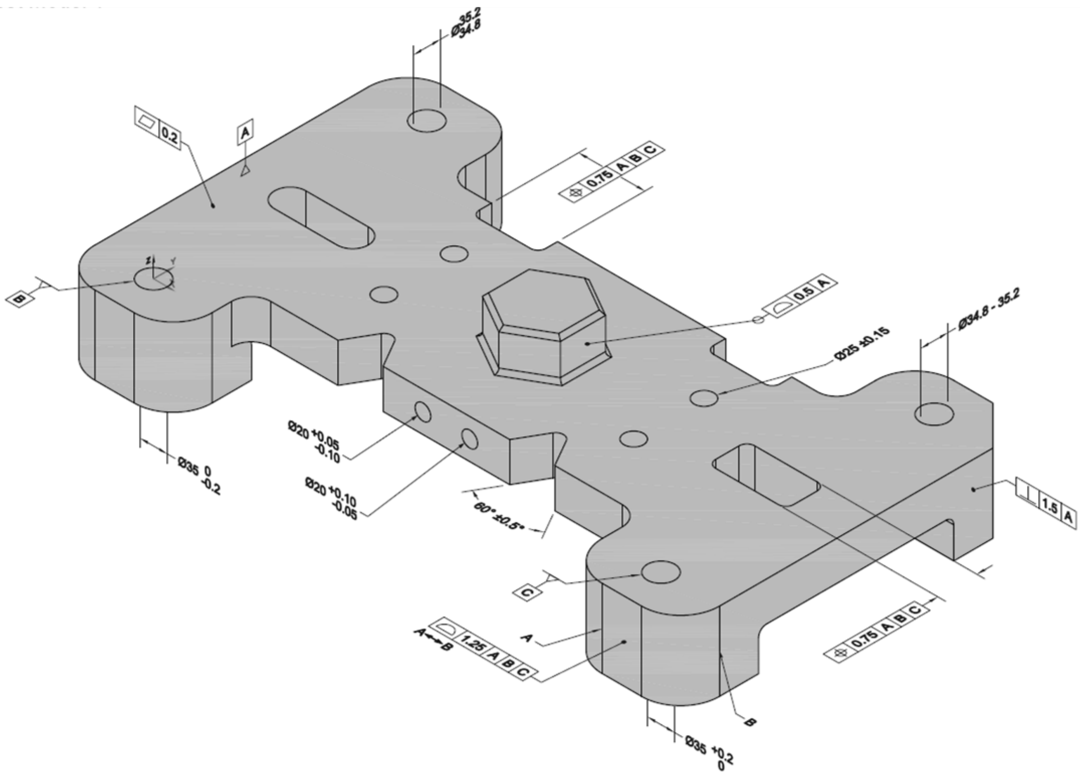


Figure 6-42 NIST PMI artefact, CTC 3 (NIST, 2014)**.**

The models have been released to the public, and twenty blocks were manufactured by the Manufacturing Technology Centre in mid-2014. The blocks were produced in five sets of four. Parameters including the type and manufacturer of the tool, the cutting width and depth, cutting speed, and feed rates were varied. For the purpose of the demonstration it is unimportant how they were varied, rather just that each set was produced in a similar way and that the deliberate changes to the manufacturing process were only varied between sets. One of the manufactured blocks is pictured in Figure 6-43

Three blocks from three sets were measured with low, medium, and high sampling methods. Uncertainty simulation was performed against all the PMI on the model for each set, resulting in twenty-three measurands to evaluate (Table B-14). The measurement programs were carried out on the same CMM as for CTC 2, and the same sampling methods were employed (Table 6-5), including the use of scanning to capture form error, as shown in Figure 6-44.

Figure 6-43 Manufactured artefacts, CTC 3.

The system diagram in Figure 6-45 shows how the template selection process was implemented for CTC 3. In this diagram, the boxes labelled 'measuring system characteristics', 'measurement method templates', and 'capture manufacturing signature' signify the data that was required to simulate uncertainty in the UES. The boxes labelled 'target uncertainties' and 'select method templates for operations measurement' were handled through Microsoft Excel® in the manner explained for the first demonstration (Figure 6-37 to Figure 6-40).

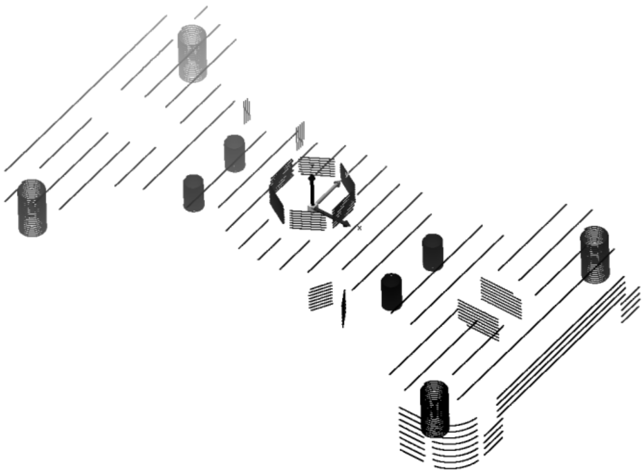


Figure 6-44 Scan points for capturing form error, CTC 3.

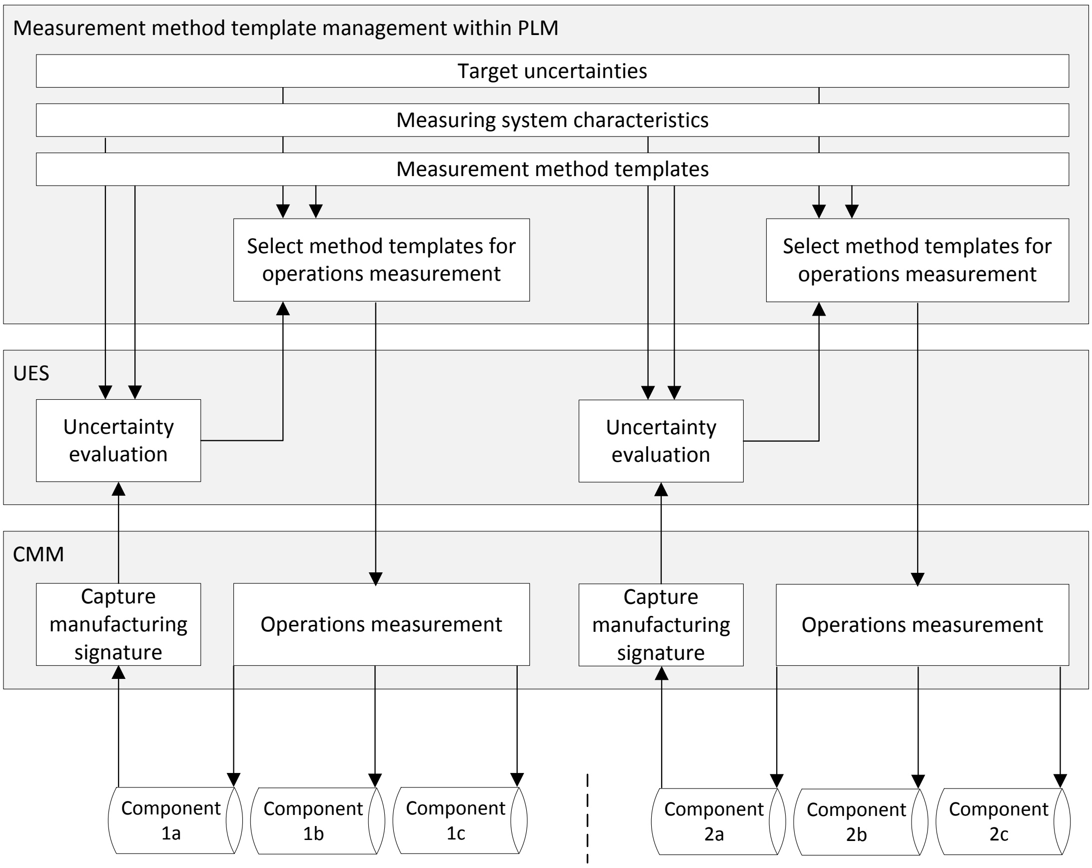


Figure 6-45 System diagram for demonstration, CTC 3.[5]

[5] This diagram was jointly developed with Dr. Bin Cai when planning the demonstration.

The process was carried out for one block from each of the three batches studied. Examples of the results from the UES simulation for each of these 'heartbeat' blocks against the target uncertainty are shown in Figure 6-46 to Figure 6-48.

These examples show the broad variety of situations that can be encountered, and the task-specific nature of the measurement planning problem.

Beginning with the cylindricity PMI (TOL15_2_CYL) shown on the left of Figure 6-46, it can be seen that whilst '1B' should be measured using the 'High' method level in order to meet the target uncertainty, no suitable method level could be found for component '4A'. On the other hand, '5A' could be measured using a 'Low' method level. Similar variety can be observed for the diameter PMI (TOL16_1_D) on the right of Figure 6-46. The graphs for profile and position PMI in Figure 6-47 show instances where the target uncertainty is met for all components, though for position, method level appears to have little impact. Finally, the graphs in Figure 6-48, show cases where the target uncertainty is more challenging to meet through varying sampling method alone.

Notably, in all of these cases, a perfectly manufactured block could be satisfactorily verified using a 'Low' method level.

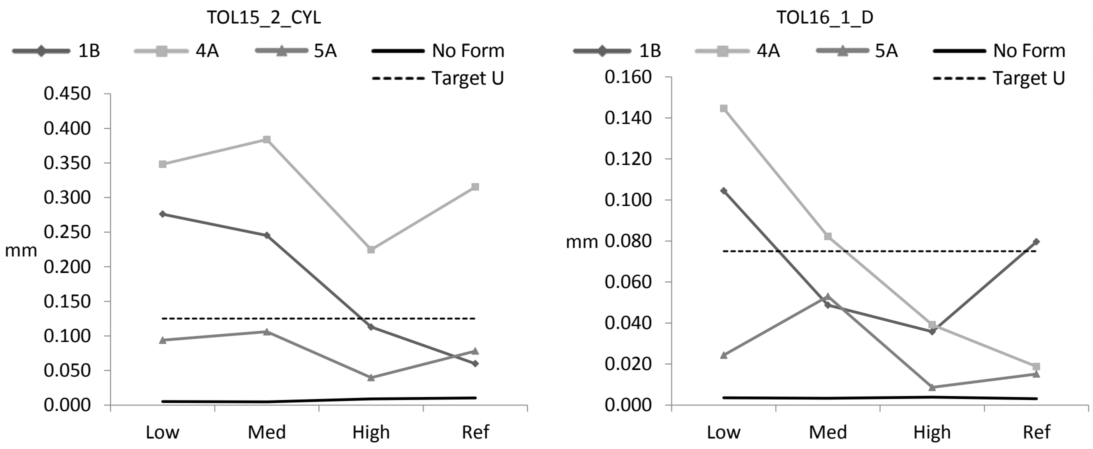


Figure 6-46 U_{sim} and U_T, cylindricity and diameter, heartbeat blocks, CTC 3.

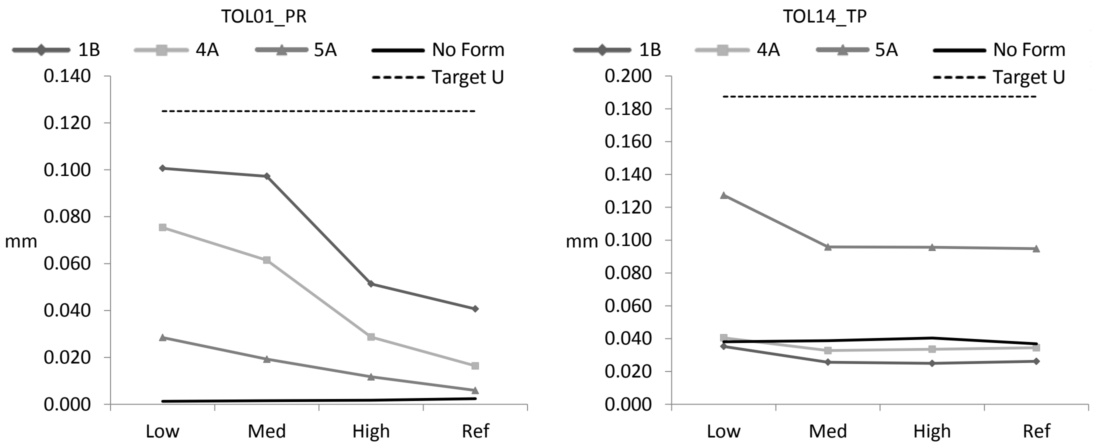
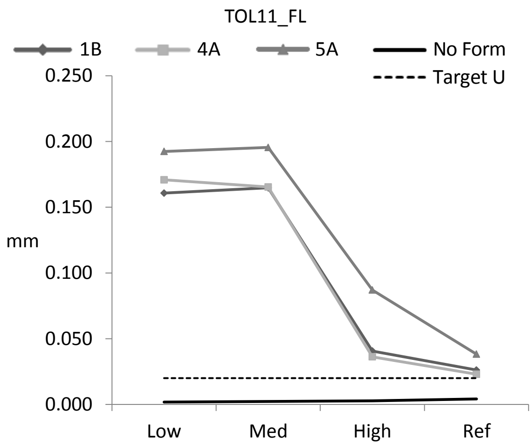


Figure 6-47 U_{sim} and U_T, profile and position, heartbeat blocks, CTC 3.



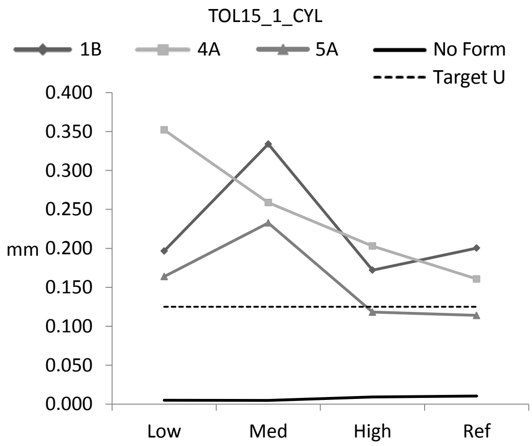


Figure 6-48 U_{sim} and U_T, flatness and cylindricity, heartbeat blocks, CTC 3.

6.7.3 Reflections on system demonstration

The purpose of the demonstrations was to build a system that can be used to develop measurement standards, and then to review the effectiveness of the system through the integrity criteria proposed in Section 6.3.3: How complete, how rigorous, and how apposite is the proposed system for measurement planning?

- Completeness

  The demonstrator provided a means to develop measurement plans for those measurands where sampling method was a strong contributor to measurement uncertainty. However, it was found that the impact of sampling method is variable, as summarised for a selection of the studied PMI in Figure 6-49 and Figure 6-50 for CTC 2 and CTC 3 respectively. These graphs show the ratio of simulated uncertainty using the reference method as compared to simulated uncertainty for the low method. The results have implications for the ability for the proposed system to provide a complete measurement planning solution.

  Firstly, it can be seen that a 'perfect' block would be a very poor substitute when attempting to simulate uncertainty for 'real' blocks with form errors.

  Secondly, it is noticeable that generalisations cannot be made by PMI type. For example, in Figure 6-49 the parallelism PMI 'TOL08_PAR' seems to be most affected by method level, contrasting with the parallelism PMI 'TOL36_PAR' for which sampling method level has little impact. Similarly, the profile PMI 'TOL01_PR' and 'TOL07_PR' in Figure 6-50 are also at opposite ends of the spectrum.

  Thirdly, there are significant variations even between the same PMI instance across different components, as can be seen for 'TOL43_PE', 'TOL06_DB', 'TOL19_D' in Figure 6-49, and for 'TOL03_D', 'TOL12_D' in Figure 6-50.

  These three observations all point to the necessity of performing simulation for each specific measurement task.

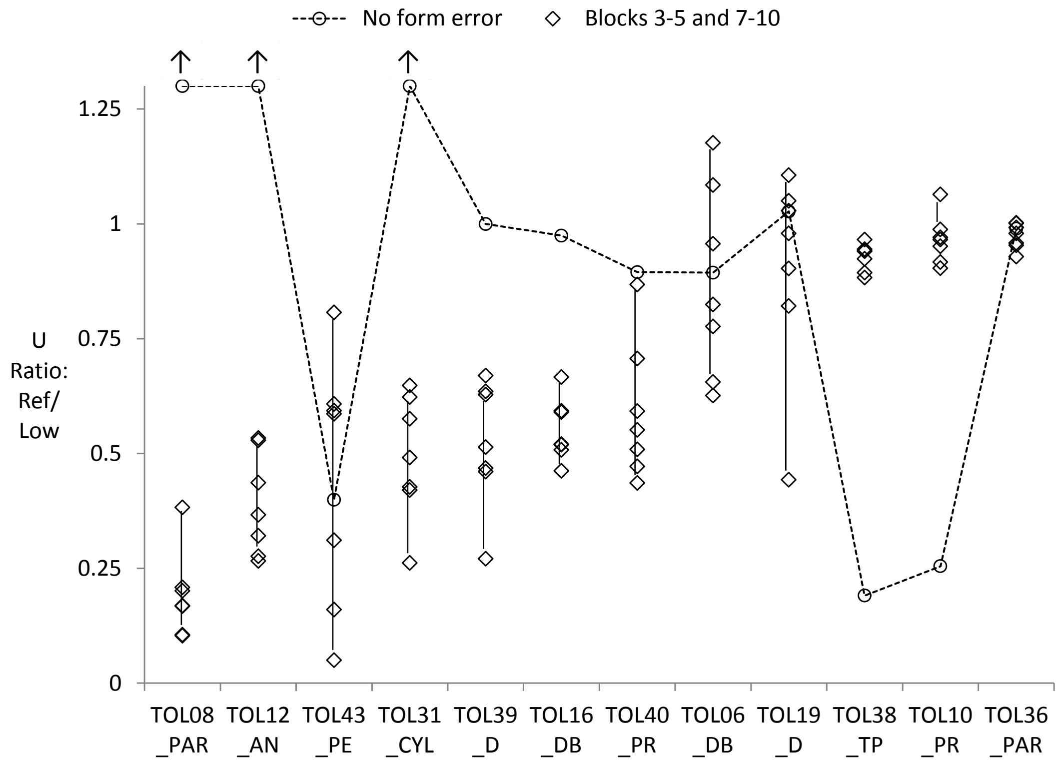


Figure 6-49 U_{sim} ratio (Reference / Low), all blocks, CTC 2.

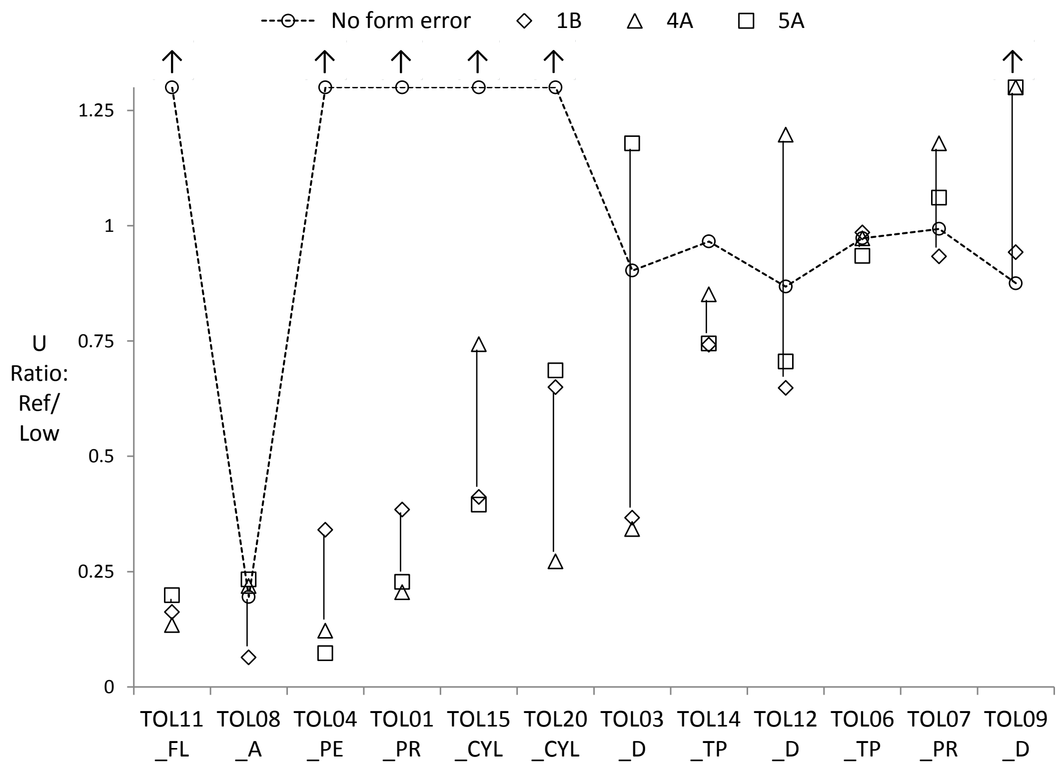


Figure 6-50 U_{sim} ratio (Reference / Low), heartbeat blocks, CTC 3.

- Rigour

  For a rigorous plan, the target uncertainty should be achievable for all the PMI on the component. Figure 6-51 shows a consolidated view of the decision matrix for CTC 3. Whilst a suitable method could be selected for most of the features, Datum A, Hole_02-All, and Hole_01A/B fell into the category of 'Review' for one or more of the studied artefacts.

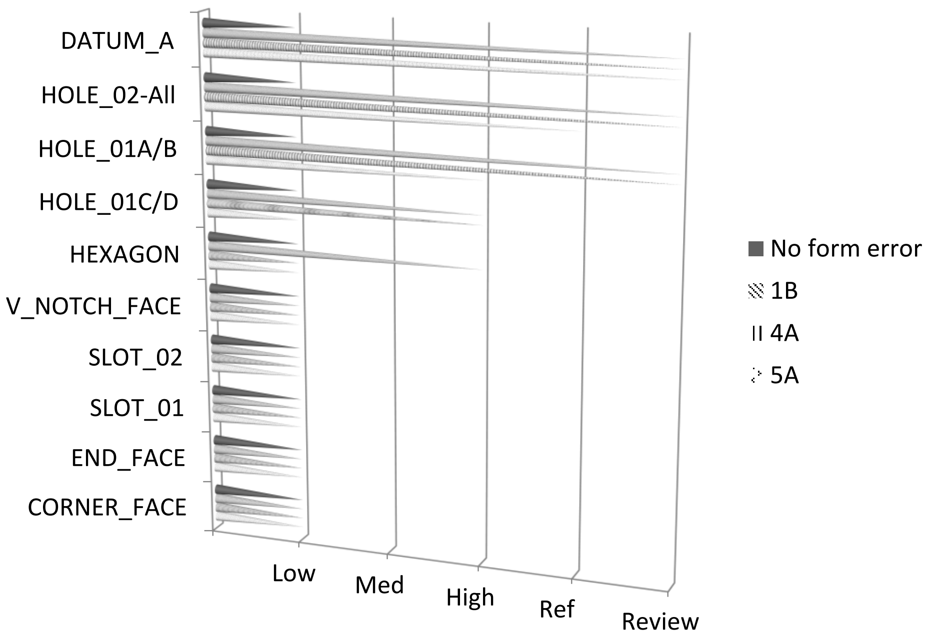


Figure 6-51 Measurability report, heartbeat blocks, CTC 3.

There are a number of reasons why a feature could need review. Firstly, the uncertainty simulation itself could be ineffective. PUMA would suggest that an attempt should first be made to improve the fidelity of the simulation by gathering more data, or changing more variables (in the demonstration, only sampling strategy was varied). Secondly, the form error may be too great. If this were found to be the root cause, it may be economic to change the manufacturing strategy rather than the measurement process. Thirdly, the tolerance may be too tightly specified.

A measurability report such as the one presented in Figure 6-51 could be generated before any measurement has been carried out. Whilst the manufacturing signatures were captured through scanning representative components in the demonstrations, other methods could have been used. Predictive methods would allow such investigations to be carried out prior to actual measurement, and is considered to be a key benefit of the proposed system, allowing 'unmeasurables' to be identified – though not necessarily their causes.

- Appositeness

  Appositeness is concerned with balancing the rigour of the measurement plan with its cost.

With this objective in mind, it might be considered informative to review the percentage of PMI requirements that would be met when using each method level. A summary for both CTCs used in the demonstration is shown in Table 6-6, with more detail in Figure B-22 and Figure B-26.

Table 6-6 Percentage on target by method level, CTC 1 and CTC 2.

Method level		CTC 1	CTC 2
1	Low	67 %	84 %
5	Medium	67 %	71 %
10	High	58 %	71 %
10*	Reference	65 %	

For both cases, increasing the method level from low to high actually led to lower acceptance rates. This has implications on the business case for higher integrity measurement. It would be insufficient to consider only the cost of the measurement process itself and its impact on part acceptance when developing a measurement standard. Costs associated with allowing a non-conforming part to be accepted must be included.

6.8 Composition of a commodity-specific measurement standard

Based on the experience of developing the demonstration system and discussions with stakeholders following the research carried out for this chapter, a picture of the requirements for a commodity-specific measurement standard can be drawn up, highlighting the requirements for future research. This is shown in Figure 6-52.

It is suggested that a measurement standard should not be regarded as static. Rather, it comprises three main processes: Objective setting; management; and validation.

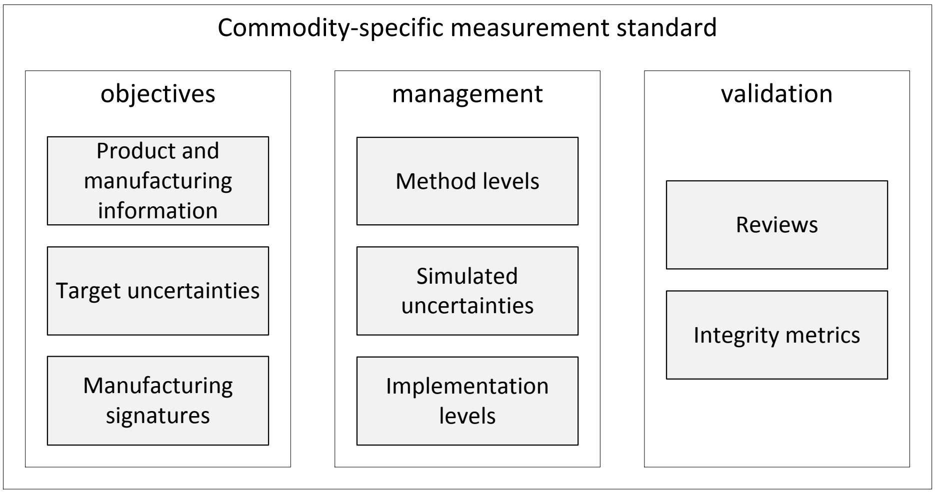


Figure 6-52 Composition of a commodity-specific measurement standard.

Objectives should be set on a measurand by measurand basis. PMI is a useful mechanism for communicating requirements, and may also be used to derive a target uncertainty. The research in this chapter showed that the manufacturing signature is of key importance when setting objectives for measurement, since standards need to be coupled to manufacturing in order to be effective. Thus research is required in understanding how best to derive target uncertainties, how to capture manufacturing signatures, and how frequently the signatures should be reviewed.

In order to develop an effective plan, a set of method levels and implementation levels need to be created. It is anticipated that experts are required in order to do this. UES would then be required to model the measurement errors that may arise from combinations of different method and implementation levels. UES is currently limited in the technology that it supports, and will need significant development in order to model, for example, dynamic errors associated with scanning, or measurement errors associated with non-contact measuring systems.

Finally, a means to validate the standard on a regular basis is important, for which integrity metrics were proposed. In many cases, particular measurands may need to be reviewed. Reports should be built up over time and used in practice in order to find out what data is most useful to inform reviews in multi-disciplinary environments.

Following a discussion of these issues with the stakeholders, it was commented that in order to develop the system further, a data model and workflow will need to be agreed. Standards such as the quality information framework could be important for the data model, whilst experience within real organisations could inform the workflow. It was suggested that one means to gain experience could be through setting up a 'strategy evaluation bureau' for small and medium sized enterprises.

6.9 Summary

This chapter was aimed at the fourth objective of the EngD, which is to create a system for developing commodity-specific measurement standards for CMMs. In order to achieve this, the question naturally arises as to what a measurement standard should comprise. To investigate this topic, the concepts of uncertainty management were explored, with an emphasis on sampling strategy. A new concept of 'integrity reports' was proposed as a means of assessing the effectiveness of the proposed system.

In particular, three questions were addressed, the first of which is as follows:

Do different sampling methods lead to different results?

Following an extensive set of tests on two CMM systems, it was found that whilst different results were obtained through using different sampling methods, patterns could not clearly be distinguished and the importance of form error was highlighted. This finding led to a second question:

Can reliable uncertainty statements be generated?

Simulated uncertainty values from UES were combined with the results obtained through measurement and tested against the integrity measures for uncertainty management. Whilst there were some exceptions, the results were encouraging, though knowledge of form error was found to be prerequisite. A third question was then addressed:

How effective is the proposed system for developing standards?

Two further test cases were developed, and the results were assessed against the integrity measures for measurement planning. The demonstrated system provides a scientific basis for selecting between alternative sampling strategies; potentially saving time and money during measurement, and improving confidence in the measuring system. In addition, the system allows features to be categorised according to their ‘measurability’; providing quantitative data for verification and process planning, or further upstream in design.

In summary, the attempt to find out what comprises a measurement standard, resulted in a system in which a measurement standard is linked with both the design requirements and the manufacturing process. PLM has an important role to play in facilitating these relationships. Perhaps counter-intuitively, it was found that in order to achieve consistent results and consistent rigour in measurement, there would need to be a degree of flexibility in the methods used.

Chapter 7 Industrial case study: Deploying PLM-integrated dimensional measurement at Rolls-Royce plc

7.1 Introduction

The fifth and final objective of the EngD is to determine priorities for improved integration of measurement standards with PLM at Rolls-Royce plc.

7.2 Problem definition

By early 2012, PLM had become deeply embedded into the design and manufacturing system at Rolls-Royce plc, though dimensional measurement had been left largely isolated (Lubell et al., 2012, pp. 84–88). In fact, the lack of focus on bringing measurement technology into PLM was becoming increasingly noticeable, particularly to measurement specialists who would frequently find themselves on the critical path (Orchard, 2011a).

Parallels between measurement and computer-aided manufacturing can be drawn, and are illustrated in Figure 7-1 (adapted from Lubell et al., 2012, p. 86, and extended to show measurement items, such as 'inspection plan').

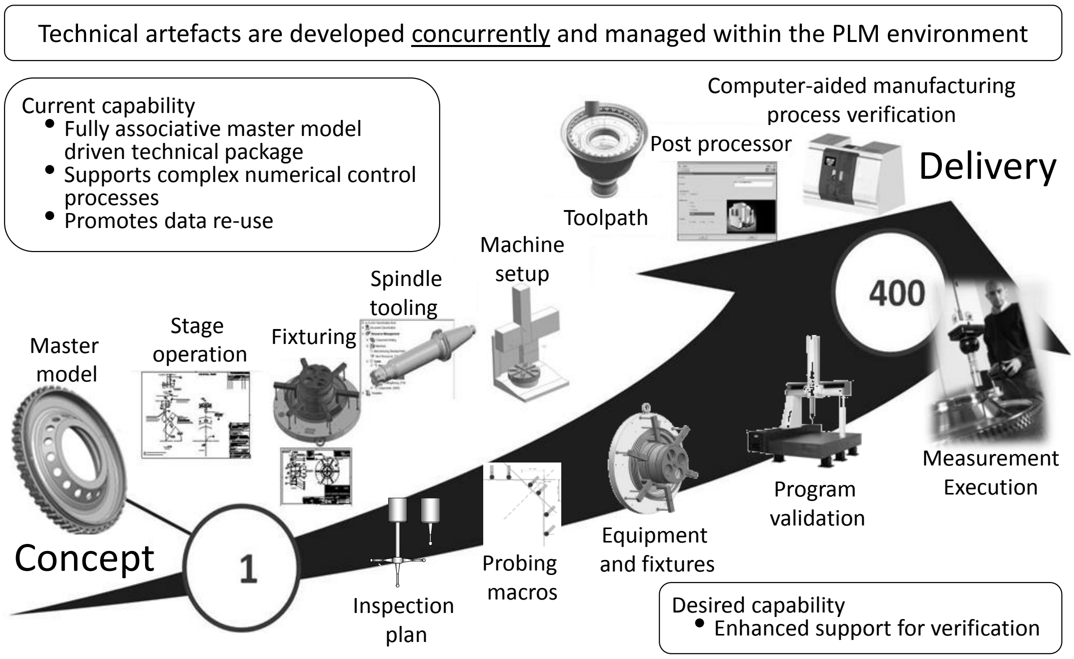


Figure 7-1 Vision for integrated measurement at Rolls-Royce plc.

The portion of the diagram above the arrow in Figure 7-1 illustrates the current situation for computer-aided manufacturing, in which an integrated workflow is built up from a master model through to verified manufacturing processes.

The numbers '1' to '400' are indicative of the increasing numbers of technical artefacts which are generated and associated within an integrated data structure as the process matures; these would include items such as stage models, fixture models, tooling information, and machine setup files.

The portion of the diagram below the arrow illustrates a vision for measurement, which it is felt would be a suitable starting point for answering the following question:

> *How should measurement standards be deployed within PLM to maximise value for Rolls Royce plc?*

7.3 System model showing current state of measurement integration

In order to better understand the current state of integration, a focus group was formed with representatives from systems, measurement, and component design. Since this was a new area at the time, there was no formal budget for the activity; thus, the fact that individuals were motivated to contribute is an indicator of the importance these individuals placed on the issues.

Three major alternatives for change were identified; their advantages and disadvantages are listed in Table 7-1:

Table 7-1 Alternative PLM-integration strategies.

Integration strategy	Advantage	Disadvantage
Native	Integration would happen by default. Updates could be managed centrally.	There would be a delay in support for new measurement technologies. Metrology solutions are unlikely to be optimised, since the software would drive systems that have been created by other vendors. Full automation would be unlikely to be achievable.
Custom interface	There would be a high understanding of the metrology challenges and a high level of support.	It would be difficult to keep pace with changes to the PLM environment – both commercially and technically.
Open standards	There would be potential to interface to a wide range of supported software.	Interfaces within the connected software would require a high level of maintenance and regression testing. Standards are currently immature.

In the light of these potential advantages and disadvantages, the ‘native’ solution was deemed by the group to be suitable for consideration first. It was therefore decided to request a demonstration of the state of art from Siemens, the PLM vendor at Rolls-Royce plc. The objective of the demonstration was to answer the simple question:

> *Is a native PLM-integration strategy worth exploring?*

This was not a new issue. In 1988, Rolls-Royce plc began the search for a tool to allow measurement programs for coordinate measuring machines (CMMs) to be created from CAD. Indeed, an internal technical report from 1993 (TSR 1844) identified approved ‘CAD/CAM inspection’ software for Rolls-Royce plc following an extensive study of four competing solutions. A leading solution was implemented, though internal reports showed it to be disappointing ('not very easy to use … training and support is poor'; 'those who have used it find it easier to write programs manually'). However, since there were a growing number of commercial products that were becoming available in this domain and it appeared to be a good time to reassess.

A total of four half-day meetings were held to review existing process documents and capture the current state. The key quality standard in this domain begins with an inspection plan and ends with a measuring system ready for use in production. Other documents include guidance on how to perform a risk analysis on the verification of dimensional characteristics; still more documentation was available to describe the process of capturing measurement results. However, it was found that no document existed to show the location of all dimensional measurement activities within the lifecycle of a component. The group therefore prepared an activity diagram, which was reviewed in three further workshops and presented to the measurement community of practice for comment. As a result of the reviews, a number of changes were made to the diagram; the final model, representing the shared view of the focus group and other stakeholders, is shown in Figure 7-2. (The circled letters will be explained in Section 7.4.)

The model is documented in unified modelling language (UML) and has three partitions. (Fowler, 2004, provides a good introduction to UML and its terminology.) The 'PLM' and 'external to PLM' partitions are used to highlight opportunities for increased integration. The 'other' partition was added to show additional areas of complexity that will need to be considered in the future, although these were excluded from the main partitions to avoid cluttering the diagram; however, these items do in fact represent a considerable challenge.

Differing from standard UML, the boxes on the model represent technical artefacts (such as a model, drawing, plan, or program), rather than processes (such as 'approve drawing', or 'create program'). The activity diagram was documented in this way because it is the existence of these technical artefacts, rather than the processes, that signal progress through the component lifecycle; this has also been observed by Eppinger (2001) when considering the process of design. The processes that are used to transform inputs to outputs are more variable between the diverse businesses to which the model applies, than the technical artefacts that are required.

Beginning with an engineering 3D model, the activity diagram shows how the company is dependent on engineering 2D drawings, as well as additional manufacturing drawings that are needed for different operations during manufacturing. The drawings are then 'ballooned' – this means that identifiers are added to each characteristic that needs to be verified. At the time of developing the model, the ballooning process occurs outside of PLM. That is to say, that if a change is made to the model or drawing within PLM (for example, a feature is changed or a new feature is added), this would not be automatically associated with the ballooned identifier; a process to manually update characteristic identifiers would therefore have to be enacted.

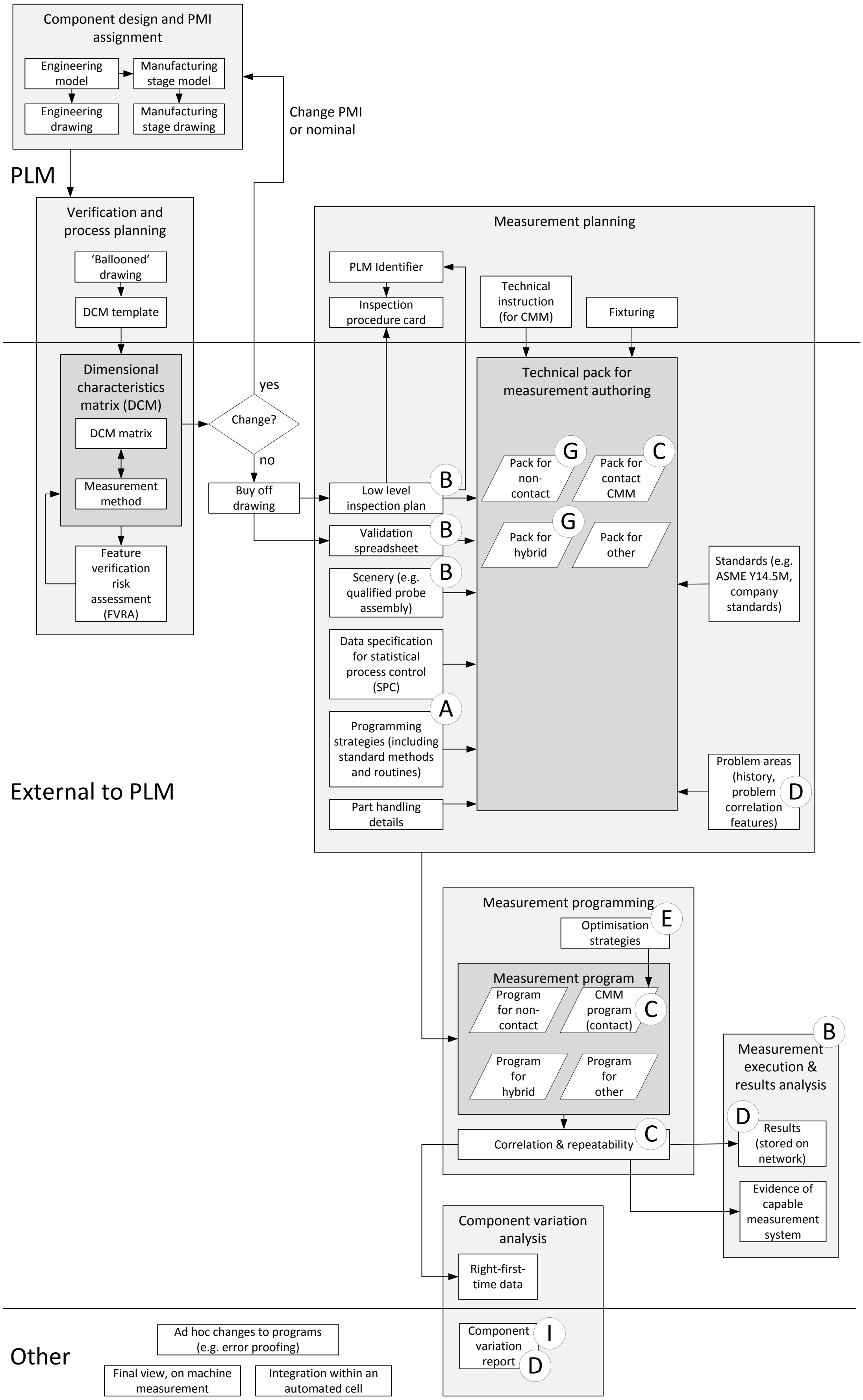


Figure 7-2 Current state of integrated measurement at Rolls-Royce plc.

From this point forward there is very little interaction with PLM, even though other manufacturing process planning activities, such as for machining or robotics, are highly connected to PLM. Following ballooning, a dimensional characteristics matrix is developed (marked as 'DCM' on Figure 7-2). The characteristics matrix is used to document the plan for how every dimensional characteristic will be verified. It is developed iteratively between design, manufacturing, and measurement stakeholders.

Once the matrix is agreed, together with any associated changes to models and drawings, the plans are 'frozen' and a technical pack for authoring measurement programs can be created. This is a manual activity that requires a considerable amount of experiential knowledge, since the pack needs inputs from a diverse range of sources. Once the technical pack is assembled, a measurement program is created and validated ('correlation and repeatability'); in order to achieve this, typically a second program is written by an independent programmer. Finally, evidence that the system is capable is stored locally, and the results from production measurements are stored on the network as evidence of product verification and for use in reporting metrics such as Right First Time.

Figure 7-2 was later overlaid with boxes (shown in light grey) indicating steps from the PiDM workflow, showing how the theoretical framework developed in Chapter 4 relates to industrial practice.

In addition to the activity diagram, a set of functional requirements were developed and prioritised. In total, there were one hundred and three requirements which covered the following areas: CAD interface; programming environment; offline programming; programming tools; probe management; program execution; calculation of results; reporting, data storage and retrieval; and probing system specific issues.

A compressor disc was acquired, and was used as the subject for the demonstration. PMI was added to the component by a Rolls-Royce plc designer. A set of scenarios were developed, that were viewed to be the main modes of operating a CMM measurement program within Rolls-Royce plc: Inherit PMI; create PMI ('on-the-fly'); no PMI; no model ('teach-and-learn'); and PMI check (e.g. to ensure PMI is complete and does not contain duplicate or conflicting requirements prior to the creation of a measurement program).

Finally, it was decided that expert feedback, from CMM programmers with experience in different systems, would be the best way to determine the success of the demonstration. Accordingly, seven individuals with CMM programming experience from across a range of product types participated.

In May 2012, a three-day demonstration of Siemens NX CMM software to Rolls-Royce plc showed the feasibility of generating CMM measurement programs directly from 3D models. The demonstration was performed on a production model and (scrapped off) physical part. The measurement was performed on a Nikon CMM with a Renishaw scanning system (it was in fact CMM C, as encountered in Chapter 4 and Chapter 6 – see Table 4-6). The part had a number of challenging features which were successfully measured, as shown in Figure 7-3.

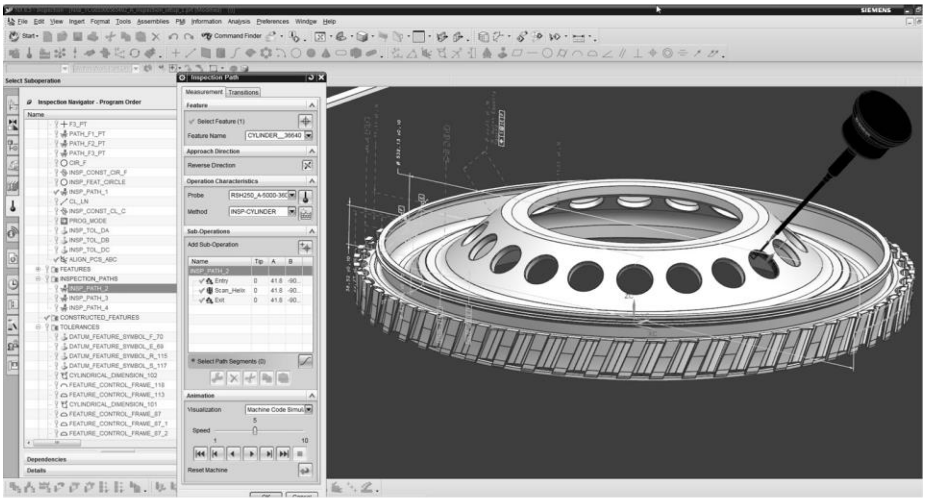


Figure 7-3 Siemens NX CMM demonstration.

In this regard, the demonstration provided a good level of confidence in NX CMM as a program generation tool. Feedback from the participants was unanimously positive; as stated by a member of the leadership team ‘it is rare to hear such consistent support’. From a technical perspective, the technology was perceived to be mature, and the opportunity for reuse of measurement methods was highlighted as a key potential benefit.

However, the demonstration was unable to answer all the questions that were put to it in the short time available. Some technical aspects could be addressed in a generic way, and led to the research described in Chapter 4 and Chapter 6. In parallel, the author carried out company-specific research in order to understand the application of PLM-integrated dimensional measurement to the products and processes at Rolls-Royce plc.

7.4 Value proposition for future PLM-integrated dimensional measurement

It was determined that the first stage of the company-specific research should be to understand the value proposition. Thus, a one-day scoping workshop was held in May 2013, just as the first phase of the generic research described in Chapter 4 was nearing completion.

In preparation for this workshop, eight business representatives were requested to complete problem and opportunity templates (Figure C-1 and Figure C-3):

1. What problems could the integration of measurement processes with PLM help with?
2. What is your vision for the full scope?

From this survey, forty-one problems and twenty-nine opportunities were identified. The problems and opportunities were categorised and a Pareto analysis was performed. Finally, any issues that were considered to be of ‘low’ priority were eliminated. This resulted in a core of eight problems and seven opportunities. Finally, definitions for each of the problems and opportunities were refined based on the written feedback; these definitions are provided in Figure C-2 and Figure C-4.

During the scoping workshop, each representative delivered a fifteen minute presentation on their issues. After listening to all the presentations, the workshop participants fed back their primary areas of interest. Overall, fourteen participants provided feedback using the template shown in Figure C-5. The feedback uncovered nine focus areas. A count of the number of times they were mentioned is shown in Figure 7-4. Four of the top focus areas were then mapped to the problems and opportunities that had been highlighted in the completed templates, thus validating coverage and informing priorities. The mapping is shown in Figure 7-5.

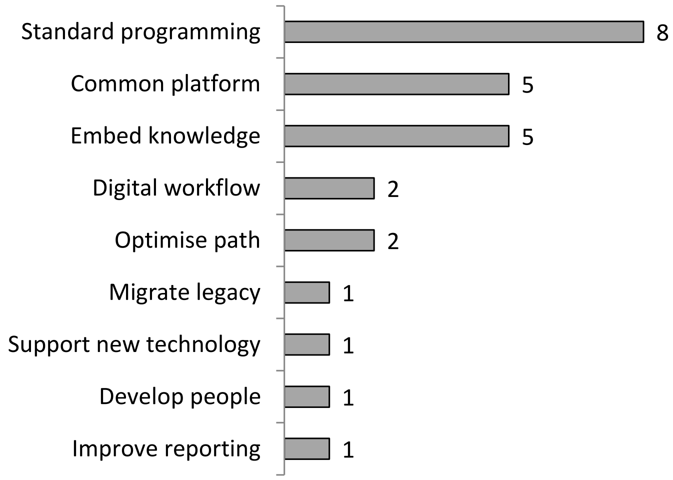


Figure 7-4 Results of focus questions.

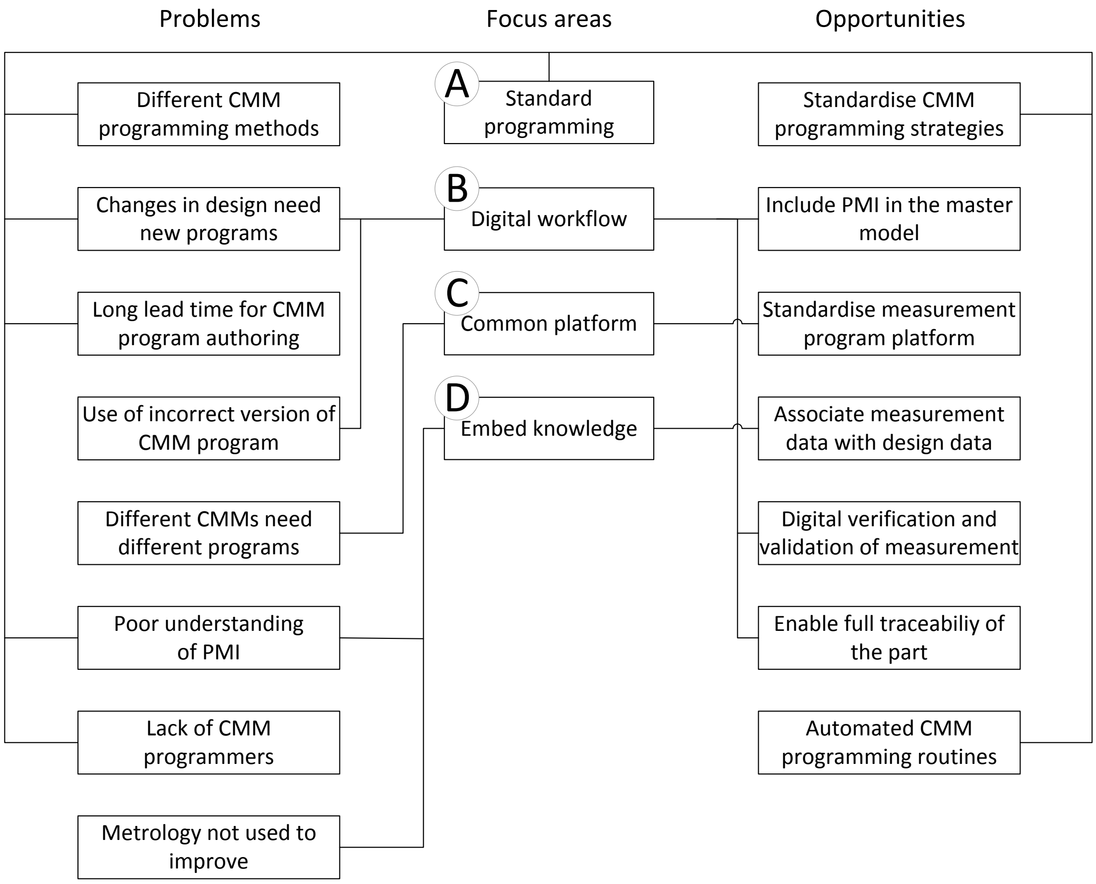


Figure 7-5 Mapping focus areas to problems and opportunities.

The entire workshop was recorded with consent from the attendees. This has allowed the author to review the discussions that took place and propose a description for each focus area. These descriptions have been further refined following feedback from the workshop participants.

The descriptions for four of the top areas are as follows:

A. Standard programming (contact CMMs)

   Embed best practice knowledge for standardising CMM programming methods within PLM, with the aim of providing consistent results. Programming methods should include point spacing, number of points, scan parameters, and typical form error. They should account for the uncertainty of the measurement task. They could, for example, be stored as validated programming templates that work intelligently with design through PMI. The focus will be on new and current methods – e.g. the use of scanning probes, and treating CMMs as 'point collectors' for application-specific analysis. Hyperlinks could be provided to embedded training material for clarification.

B. Digital workflow

   Migrate more of the end-to-end workflow to the digital environment, i.e. the Rolls-Royce PLM deployment, with the aim of improving concurrent development, traceability and change management. Aim to align with the *Quality information framework* (DMSC, 2013).

C. Common platform

   Use a single platform to author and develop CMM programs, to enable a 'CMM program regardless of CMM brand'. This approach, coupled with the use of uncertainty evaluation, may also enable a less costly way of performing independent validation. The objective is to facilitate the reuse of programs.

D. Embed knowledge (Measurement for design)

   Associate relevant measurement results with PMI in the model to enable initiatives such as design for manufacture. Note that this means understanding what measurement data is required by other groups, such as design. This should incorporate feedback for correcting the model, and feedback to better understand PMI. A key objective should be to move from verification of PMI to validation (where validation is defined as verification *for an intended use*); this will help determine which areas to target in manufacture and measurement in order to eliminate waste.

Five other areas were also identified, as follows:

E. Optimise path

   Optimise probe paths and tool changes to gather data more efficiently - not necessarily feature-by-feature.

Note: Although this focus area scored equally with [D] 'Embed knowledge', it did not map strongly to the problems and opportunities which had been identified.

F. Migrate legacy

Integrate existing measuring systems and software with PLM, to be assessed on a case-by-case basis.

Note: The relevance of this focus area was questioned by two participants in the feedback.

G. Support new technology

Include support for non-contact, and predominantly multisensory devices. Incorporate processing and integration of point cloud data. Consider focussing on new projects, including the repair of fan blades and rapid manufacturing.

H. Develop people

Train measurement specialists in the use of PLM, and computer-aided manufacturing specialists in measurement. There should be opportunities to both inject 'new blood' into metrology as well as make use of the existing PLM expertise within computer-aided manufacturing. This is also important to address the growing skills gap.

Note: Subsequent feedback has suggested this area should be given a higher priority.

I. Improve reporting

Incorporate a multi-perspective approach to measurement, so that programming and data are targeted to the needs of specific user groups – for example, feedback of relevant measurement data to design engineering. Ensure reports are standardised and compatible with customer systems.

The focus areas (with the exception of [F] and [H]) were mapped back to the process diagram, as shown by the circled letters in Figure 7-2. Noticeably, all of the focus areas that were identified are currently outside of the PLM partition.

7.5 Impact statement

Following the identification of focus areas, individual semi-structured interviews were conducted to identify suitable test cases, potential contribution, validate priorities, and understand other contextual issues. Five interviews of approximately one hour duration were conducted; three face-to face; two by telephone. Two other representatives answered the survey questions in written form. Whilst it was noticeable that three of the representatives expressed a desire for blade geometry to be emphasised, it was clear that problems still needed to be addressed on prismatic features. In no case were test cases suggested in which models already existed with PMI, thus the creation of PMI would need to form a central part of any future work.

Overall, the findings from this research has provided input necessary to persuade senior management of the need for a multi-year multi-partner project for Rolls-Royce plc that has begun in mid-2014. The project is not aimed at deployment; rather, it is identifying how mature, and how capable the technology is to address the gaps.

The technology gaps are being assessed using the theoretical framework for PLM-integrated dimensional measurement (Chapter 4), which is also being co-evolved. With that goal in mind, three complex test cases (as defined in Section 6.4.3) are currently being defined, thereby extracting value from the research in this thesis.

7.6 Summary

The study reported in this chapter attempted to address the fifth objective of the EngD, which is to determine the research priorities for improved integration of measurement standards with PLM at Rolls-Royce plc. A focus group was formed to address the issue, and began by modelling the current workflow and documenting the challenges that are faced. It was found that dimensional measurement processes are not associated with the deployed PLM environment at Rolls-Royce plc. There was no feedback of measured geometry into PLM; neither was there any formal process to feed-forward design and manufacturing data (such as the criticality of a verification requirement) to measurement processes. When changes occur in a design or manufacturing model or drawing, processes would take place outside of PLM in order to inform measurement. As a result, dimensional measurement processes are isolated from the design and manufacturing processes they support.

The value that closer integration with PLM could bring was therefore investigated.

Nine potential focus areas were uncovered, of which four were identified as being of highest priority – these are as follows:

1. To enable the standardisation of measurement methods;
2. To migrate measurement processes to a digital workflow;
3. To rationalise measurement, avoiding having multiple competing processes for similar tasks, and;
4. To foster links between PMI and measurement processes through association in PLM.

In short, it was found that there is a considerable amount of change needed in order to fully integrate measurement standards with PLM at Rolls-Royce plc. The research has helped to put in place the foundations for a substantial project to further investigate the issues and to develop a deployment strategy. The initial implementation could be several years away; in the meantime, a tactical solution may be more appropriate, and this will be discussed in Chapter 8.

Chapter 8 Links between engineering design and measurement technology

8.1 Introduction

This chapter contains a critical discussion of the findings from the EngD research in relation to extant literature and the state of art. The chapter is divided into two parts. In the first half, the findings are organised according to their role in linking engineering design and measurement technology. The second half is a discussion of how these links could be strengthened in the near term; the proposed approach also allows the findings from the research to be exploited by organisations which do not have the benefit of a comprehensive PLM environment.

8.2 Mechanisms that link engineering design and measurement technology

In the course of the research, a number of themes were investigated that were identified from the literature review, stakeholder analysis, and through the author's own studies, as important in the relationship between engineering design and measurement technology. The relationship is complex. Indeed, in a report for the National Measurement Office, nineteen mechanisms were identified which deliver economic returns from measurement – many of which incorporate design processes, such as 'better decisions', 'better standards', 'enabling a new product' (Swann, 2009, p. 87).

One means to make sense of complex relationships is through the use of an influence diagram (Senge, 2006, pp. 68–91). An influence diagram is a way of diagramming causal links between variables; because it can show mutual causality, it is well suited to illustrate feedback and dynamism. The technique is used in Figure 8-1 as a means of abstraction and to provide context for the subsequent discussion in this chapter.

The variable 'number of unmeasurables' is shown at the top of the diagram; this is the unwanted emergence that the EngD research is attempting to address. There is a dotted arrow arriving from 'measurement consistency' to indicate the belief that there is a negative correlation between consistency and unmeasurables. That is to say, more consistent measurement is expected to result in fewer unmeasurables; likewise, there is an expectation that less consistent measurement would result in more unmeasurables. All of the other arrows in the model have solid lines and represent positive correlations. For example, an increase in the application of measurement standards is expected to lead to an increase in measurement consistency and vice versa.

On further examination, three loops can be identified. Since all the correlations are positive, they are termed as 'reinforcing' loops; this means that without any external influences, variables within the loop will tend to increase or decrease depending on their initial direction. In reality, of course, there are external influences and links that are not shown on the model; nonetheless, it provides a useful means to highlight links which should be encouraged.

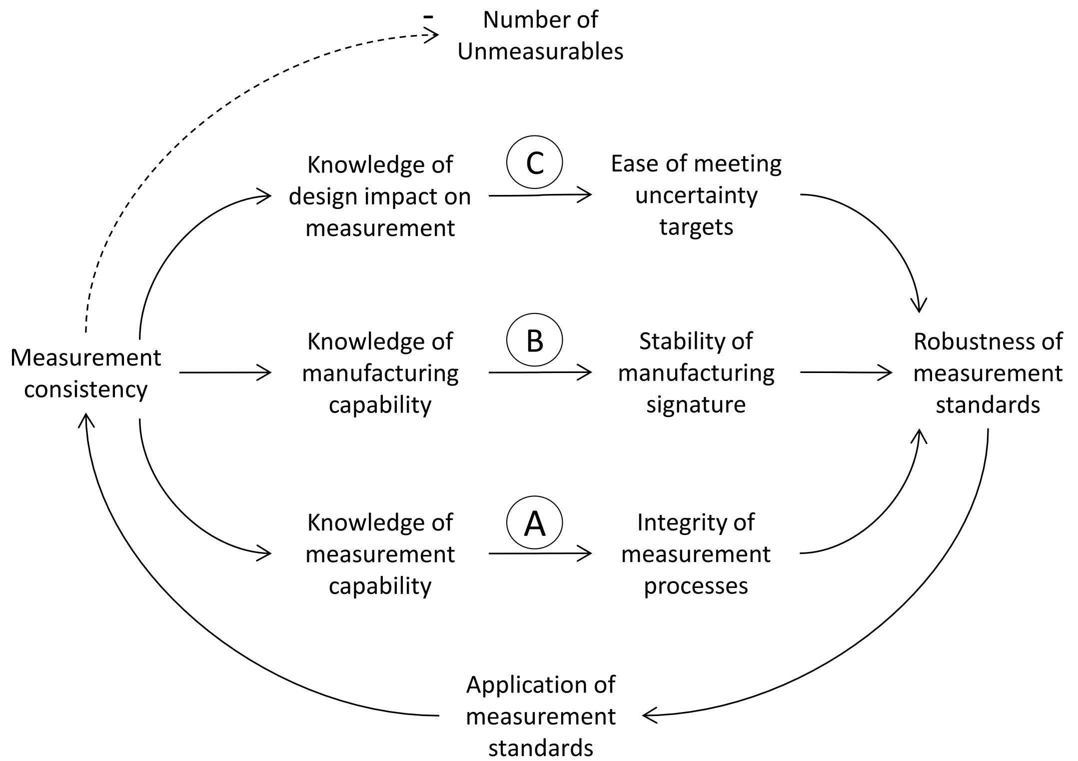


Figure 8-1 Reinforcing loops relating measurement standards and consistency.

All of the loops go through the variables 'robustness of measurement standards', 'application of measurement standards', and 'measurement consistency'. There is a strong tradition in the literature and within practice that promotes the use of standards to improve the consistency of processes, such as in lean manufacturing (Womack et al., 1990, pp. 48–69) and six sigma methodologies (ISO 13053-1, 2011), thus the author does not believe this to be a contentious point of view. The discussion in this section will therefore concentrate on the three routes through which it is argued that measurement consistency can result in robust measurement standards. Starting from the bottom of the Figure 8-1, these are as follows:

A. Knowledge of measurement capability;
B. Knowledge of manufacturing capability;
C. Knowledge of design impact on measurement.

8.2.1 Knowledge of measurement capability

Measurement consistency was defined for the EngD research around the concepts of consistent results and consistent rigour (Section 5.5.2). Results are regarded as more consistent when the uncertainties associated with measured values are similar for the same measurand, no matter how, where, when, or who performed the measurement. Consistent rigour adds the additional requirement that the measurement uncertainty for *every* measurand is known. Therefore, by definition, improvements in measurement consistency will result in a better knowledge of measurement capability.

According to the total uncertainty model, measurement uncertainty is made up of method uncertainty and implementation uncertainty (ISO 17450-2, 2012). Under the duality principle (Section 2.5.1), the metrologist should be entirely responsible for implementation uncertainty, since it is concerned with the difference between the selected verification operators and a perfect verification operator (ISO 8015, 2011). On the other hand, method uncertainty is caused by the difference between specification operators and verification operators, and thus it could be argued that the designer and the metrologist have joint responsibility; indeed, method uncertainty could be regarded as *the* link between design and measurement.

Srinivasan (2003) advised that there are three main sources of differences between specification and verification within duality which contribute to method uncertainty: extraction, filtration, and association. In the EngD research, a system was built in to explore the impact of dissimilar sampling methods on measured values and associated uncertainty (Section 6.4.2), noting that sampling is part of the extraction operator. The system made use of uncertainty evaluating software, as recommended by national measurement institutes (Section 2.4.4). As predicted by theory, differences could be clearly discerned and were great enough to suggest that different methods should be applied to different features. The magnitude of the differences, and the difficulty of predicting the impact on measurement results, did not necessarily accord with intuition; this could be an important revelation to the uninitiated.

The effectiveness of the system was measured through a set of integrity metrics (Section 6.3.3). In order for the system to score highly against the parameters set for completeness, rigour, and appositeness, a high degree of knowledge of measurement capability would be required. Moreover, given a high integrity score, one might reasonably expect to be able to improve the quality of measurement standards, as visualised in the branch labelled [A] in Figure 8-1.

The research has reinforced the importance of method uncertainty to manufacturing measurement. Although this is widely known in academia, and by measurement practitioners, there is no complete system in the market place which provides the explicit means to control method uncertainty for coordinate measuring machines. A process was proposed, together with measures for its success, which was found to be operational, thereby advancing the state of art. Whilst the individual functions required for this system have existed in commercially available systems for many years, the author is not aware of any other system in which the relevant modules have been brought together. This is evidenced from the enhancements that were required to develop the interfaces between the uncertainty evaluation software, measurement programming software, and the product lifecycle management system (Section 6.7).

8.2.2 Knowledge of manufacturing capability

A second route from measurement consistency to measurement standards is shown on Figure 8-1; this is through improving the knowledge of manufacturing capability. It is reasoned that measurement consistency will provide better information about the output from manufacturing processes, thereby potentially allowing the manufacturing signature to be stabilised, completing the chain of links in the branch labelled [B] in Figure 8-1.

This is important in the relationship between engineering design and measurement technology because the shape of the feature being measured can have a significant impact on method uncertainty; therefore the 'signature' that is imparted onto components as they are manufactured is also a key link (Section 2.4.3).

The system built in Chapter 6 demonstrated the difficulty in defining measurement standards without knowledge of the manufacturing signature. Although this is well known by measurement practitioners, this may not be so evident to designers or manufacturing engineers who have less exposure to the measurement process. Perhaps surprisingly, this critical observation of the importance of the shape of the feature being measured on measurement uncertainty is not reflected in the total uncertainty model (ISO 17450-2, 2012). Srinivasan (2003) points out that the omission of manufacturing issues from total uncertainty theory was a deliberate choice made by the architects of the duality principle; only design and measurement were considered to be sufficiently closely connected as to be linked by a common standard.

However, given the significant impact which manufacturing processes can have on method uncertainty, the author believes that this needs greater acknowledgement. For example, the use of 'blind' sampling strategies (Section 5.5.3) would seem to be unwise, yet it has been observed during the research that this is how many practitioners mistakenly interpret current guidelines. Whilst there are no prominent international standards that explicitly link manufacturing with measurement, there is no reason to refrain from incorporating the capture of manufacturing signatures within company procedures. A demonstration of how this could be achieved, using a product lifecycle management system as a mediator, was shown to be effective (Section 6.7.2).

The research has reinforced the importance of understanding the manufacturing signature when considering sampling strategy, and has provided a rich dataset of examples from a laboratory demonstration using multiple measuring systems (Appendix B). It is recommended that the process by which these examples were generated is reapplied to different applications to check the integrity of the approach for the particular industrial context being studied.

8.2.3 Knowledge of design impact on measurement

Improvements in measurement consistency have the potential to directly influence design by providing pertinent information needed to review the impact of a component's definition on measurement; this is referred to as the knowledge of design impact on measurement in the branch labelled [C] in Figure 8-1. This knowledge may be used to balance the target uncertainty, U_T, against that which is realistically achievable for each measurand, U. This goal is reflected in equation [8-1], which was also used as the integrity metric for rigour in measurement planning (Section 6.3.3).

$$|U - U_T| \approx 0 \qquad [8\text{-}1]$$

With reference to this equation, there are three strategies that could be taken in order to harmonise the target uncertainties set during design with the uncertainty which is achievable by the measurement process:

A. Strategies which focus on achievable uncertainty (U).

   The measurement process could be modified in order to influence the uncertainty associated with the measurement. For example, the sampling method could be adjusted, the measurement environment could be improved, or more capable equipment could be acquired.

B. Strategies which focus on the target uncertainty (U_T).

   One could choose to focus on the target uncertainty itself. For instance, a design study might find that the target uncertainty is lower than necessary for a non-critical feature.

C. Strategies which influence achievable uncertainty (U) and target uncertainty (U_T) conjointly.

   In this case, the aim is to reduce the *difference* between achievable and target uncertainty, rather than concentrating on just one or the other. This may be accomplished through redesign. For example, a design could be modified to provide more material on which to perform the measurement; alternatively nearby features could be altered to improve access or facilitate repositioning (Flack, 2005). Such strategies may not necessarily increase the target uncertainty – it could decrease; however, the idea would be to change the design such that the target uncertainty becomes easier to meet.

The research in this EngD has taken a measurement-based perspective, concentrating on the achievable uncertainty, as per option [A] in the list above. In order for the other two alternatives [B, C] to be given due consideration, it is necessary to consider measurement issues earlier in the product creation lifecycle, before measurement planning begins. One route to implementing such an approach is described in Section 8.3.

8.3 Proposed procedure for the prevention of unmeasurables

In Section 8.2, the mechanisms by which engineering design and measurement technology are linked were discussed. It was suggested that the following variables need to be managed: the integrity of the measurement process itself (as enabled with uncertainty evaluating software for CMMs); the stability of the manufacturing process (as facilitated through integration of measurement processes in PLM), and; the ease of meeting target uncertainties (as supported by uncertainty management procedures). Through encouraging these links, it is expected that good measurement standards can be established and applied, in turn promoting measurement consistency and reducing the number of unmeasurables.

In this section, a procedure is proposed for strengthening these links without the investment associated with the implementation of a full PLM solution. This will be achieved by invoking the measurement standard system described in Chapter 6 from within the verification and process planning step, rather than waiting for measurement planning. Specifically, it is proposed to incorporate the system within the feature verification risk assessment (FVRA) process which is mandated at Rolls-Royce plc (Section 1.4.2). The approach could be regarded as an extension to the procedure for uncertainty management (PUMA) (ISO 14253-2, 2011).

8.3.1 Extension to the procedure for uncertainty management

In the extended PUMA, the core procedure trialled in Chapter 6 remains unchanged, as shown in the middle portion of Figure 8-2. A target uncertainty will still need to be defined at point [A]. Uncertainty evaluating software will also be employed to provide an initial estimate of uncertainty for each measurand at point [B]. A set of method levels and implementation levels will need to be maintained so that the appropriate level can be found for point [C]. If no level can be identified where estimated uncertainty can be reduced below target uncertainty, then changes to the measurement principle or even the measuring task itself are considered in points [D] and [E]. The difference comes at point [F], due to the fact that the procedure is now closer connected to the FVRA process which was outlined in Section 1.4.2.

The reader may recall that in FVRA, design, manufacturing, and measurement representatives come together to assign scores for severity, occurrence, and detection – with a high score for detection indicating a potential unmeasurable. By running the simplified version of PUMA described above within an FVRA context, and potentially *during* an FVRA workshop where the scores are agreed, measurement engineers will be able to more clearly highlight problematic features – that is, those where the detection score is high – to their design and manufacturing counterparts. This would increase the opportunity to debate system-wide strategies for reducing the overall verification risk, as defined by the product of severity, occurrence, and detection scores.

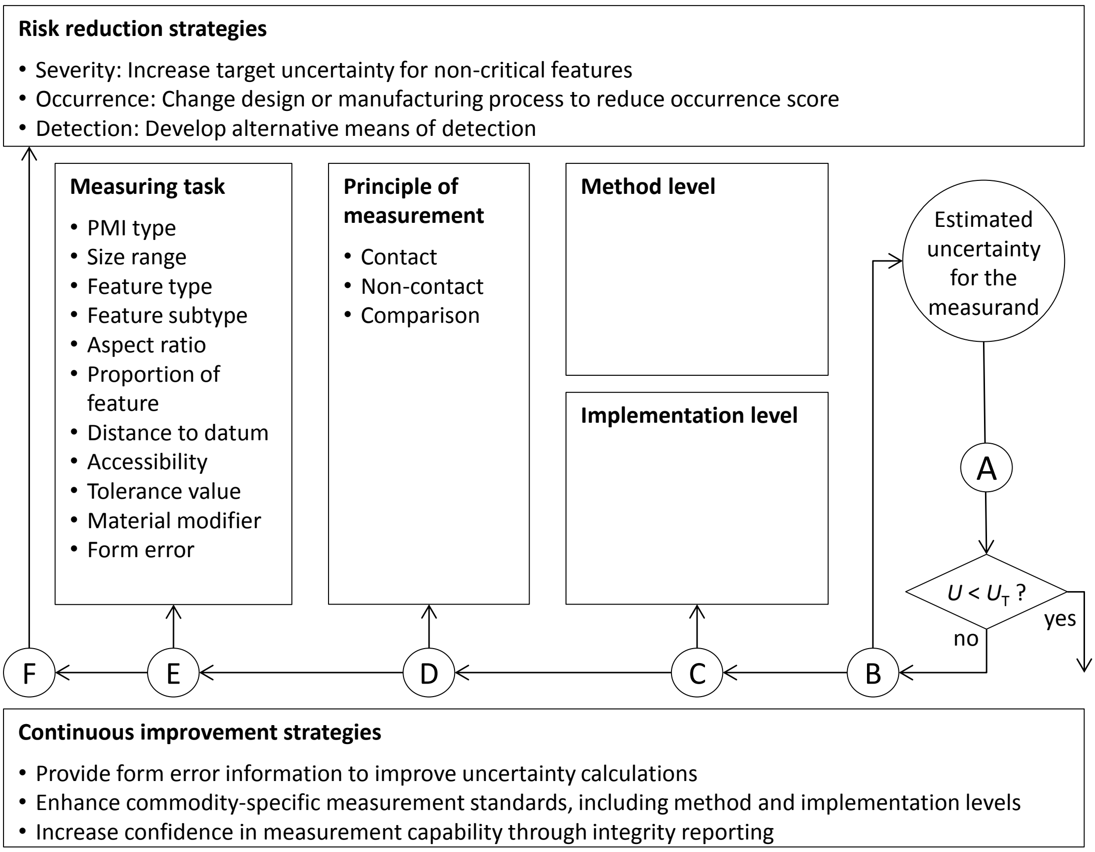


Figure 8-2 Extended PUMA, linking design and measurement.

For instance, design engineers may be encouraged to reconsider severity scores: Is the target uncertainty appropriate for this particular feature? The group would be empowered to investigate design or manufacturing changes that could be made to reduce occurrence scores. Similarly, changes in design or manufacturing could improve measurability, and more information would be available to determine the value of investing in alternative measuring systems to reduce detection scores.

As identified in the literature and demonstrated in Chapter 6, the proposed procedure is only likely to be successful if the system has good information about expected form error; the required data could be obtained from historical measurements from similar features. Additionally, task-appropriate method and implementation templates need to be maintained against which the uncertainty simulations can be run; this requires the input of metrologists. The whole system should also be closely monitored, for which integrity reports are suggested (Section 6.3.3). These connections are grouped together in the box labelled ‘continuous improvement strategies’ at the bottom of Figure 8-2.

8.3.2 Example: NIST PMI artefact

By way of explanation, a worked example is presented using the NIST PMI artefact that was encountered in Section 6.7.2.

For the purpose of the example it is assumed that it is initially expected that all verification will be performed using a CMM, and that the only machine available is the one on which this component was previously measured (CMM C in Table 4-6).

The first step in the FVRA process is already partially complete. NIST have assigned identifiers to all the geometric characteristics (NIST, 2014), as shown in Table B-14. This is not quite sufficient for an FVRA because some of the identifiers refer to multiple features (known as ‘composite tolerances’), meaning that they are related to more than one measurand. However, for the purpose of this example, only one of the associated measurands is considered in each case. The identifiers now form the rows of an FVRA table, as shown in Table 8-1.

Table 8-1 FVRA example.

ID	PMI name	PMI description		S	O	D	RPN
001	TOL16_D	Ø	Diameter of small top hole	5	1	10	50
003	TOL05_D	Ø	Diameter of large datum hole (B)	5	10	10	500
004	TOL08_A	∠	Angularity of side notch	5	10	1	50
007	TOL01_PR	⌓	Surface profile of hexagon sides	5	10	5	500
008	TOL03_D	Ø	Diameter of large non-datum hole	5	10	5	500
017	TOL11_FL	▱	Flatness of top surface (A)	5	5	10	250
021	TOL04_PE	⊥	Perpendicularity of end face	5	1	1	5
033	TOL14_TP	⌖	True position of end slot	5	10	1	50
048	TOL07_PR	⌓	Surface profile of corner	5	10	1	50

Key:	S	Severity (where 1 implies the consequence of non-conformance is not severe)
	O	Occurrence (where 1 implies that non-conformance is unlikely to occur)
	D	Detection (where 1 implies that non-conformance is easily detectable)
	RPN	Risk priority number ($RPN = S \times O \times D$)

In this example, all the features have been given a medium severity (S = 5) since there is no information available as to the functional intent of the part or the reason for each measurand.

An occurrence score has been derived from the range of ‘historical’ measurements made during the demonstration on nine components (Section 6.7.2), using the ‘high’ method level. The decision rule implemented is shown in Table 8-2. (This mirrors the rule applied in one of the earlier case studies on measurement capability, shown in Table 5-4.)

Table 8-2 Example decision rule for occurrence score.

Range / tolerance	Occurrence	Action
< 15 %	1	Acceptable if risk priority number is less than 500
15 % to 25 %	5	Acceptable if risk priority number is less than 500
> 25%	10	Review manufacturing method

The detection score was based on simulation of the representative components that resulted from the three alternative manufacturing routes used in the demonstration. For this example, it is imagined that such data might exist from previous components which belong to the same commodity type.

Depending on the highest method level required to meet the target uncertainty, a detection score was set according to the criteria shown in Table 8-3.

Table 8-3 Example decision rule for detection score.

Method level	Detection	Action
Low or medium	1	Acceptable if risk priority number is less than 500
High	5	Acceptable if risk priority number is less than 500
Review	10	‘Unmeasurable’: Review verification method

It can be seen that three measurands were found to be ‘unmeasurable’, having a detection score of ten; these are TOL16_D, TOL05_D, and TOL11_FL.

The first of these, TOL16_D, might be considered acceptable in view of the low risk priority number of fifty. Nonetheless, the measurement process appears to add little value since the target uncertainty cannot be met, thus prompting a review of the verification method.

The second measurand, TOL05_D, has a high risk priority number, though it also has an occurrence score of ten. This suggests that even if the manufacturing process is improved to reduce the occurrence of non-conformance, measurement may continue to be problematic. In this case, a review of the verification method must be completed in the light of potential manufacturing changes.

The third ‘unmeasurable’, TOL11_FL, according to the rules of FVRA, is acceptable. However, the ‘acceptance’ is only a permission to reach the next stage of planning. Measurement capability will have to be improved before first article inspection. Thus, by identifying this potential problem at this early stage, there is better opportunity to effect changes to the verification plan.

Whilst these results are, of course, artificial given the lack of information about the design intent for each feature, it nevertheless shows the potential value of implementing uncertainty analysis at this stage, rather than the more conventional approach of delaying measurement planning until verification plans are in place.

8.4 Implications for standardisation initiatives

This chapter has sought to summarise the main links between engineering design and measurement technology, as found during the EngD research at Rolls-Royce plc. In particular, an effort was made to locate the research with respect to the duality principle and the total uncertainty model; these were identified in the literature review as two of the three frameworks that link product specification and verification (Section 2.5.1 and Section 2.5.2).

A discussion was then developed around incorporating measurement uncertainty simulation techniques into verification and process planning by extending the procedure for uncertainty management (PUMA). PLM is not a precondition to such an approach; however, in its absence a neutral data structure would be required to manage the information needed in a commodity-specific measurement standard - including target uncertainties, manufacturing signatures, method levels, implementation levels, and simulated uncertainties (Section 6.8). The *Quality information framework* (QIF) (DMSC, 2013) would seem to be well suited to provide such a structure. This is feasible since QIF is early in its development lifecycle; version 1.0 was released in December 2013, and version 2.0 was released in December 2014 (DMSC, 2014a). In version 2.0, new models now exist to configure simple rules (QMRules), and to define CMM systems (QMResources). It is suggested that future research into commodity-specific measurement standards should be co-evolved alongside these new quality information standards. Indeed, QIF was identified in the literature review as the third of the three frameworks that link product specification and verification (Section 2.5.3).

Chapter 9 Conclusions and future work

9.1 Summary and contributions

The study began with an exploration of issues relating to 'measurability' at Rolls-Royce plc, and the following main research question was developed:

> *How feasible is it, using available technology, to fully plan dimensional measurement processes for coordinate measuring machines in a digital environment without conducting physical trials?*

Through a review of the literature and state of art (Chapter 2), four major gaps were uncovered, namely:

1. Methods for producing and using product and manufacturing information across the design-make lifecycle (Section 2.7.1);
2. Prediction of measurement uncertainty for coordinate measuring machines in an industrial setting (Section 2.7.2);
3. Selection of good practice when developing measurement plans for coordinate measuring machines (Section 2.7.3);
4. Framework for the integration of dimensional measurement with product lifecycle management (Section 2.7.4).

When designing the research to address those gaps (Chapter 3), it was determined that a mixed methods approach would be appropriate. Research objectives were developed which allowed the author to systematically identify gaps and mitigations in the journey from geometric specification to verification when using coordinate measurement machines (CMMs). In particular, opportunities for improvement through integration with product lifecycle management (PLM) were explored.

The two main contributions and the industrial impact of the EngD are described within Chapter 4 to Chapter 8, as outlined in Figure 9-1, and as summarised in the remainder of this section.

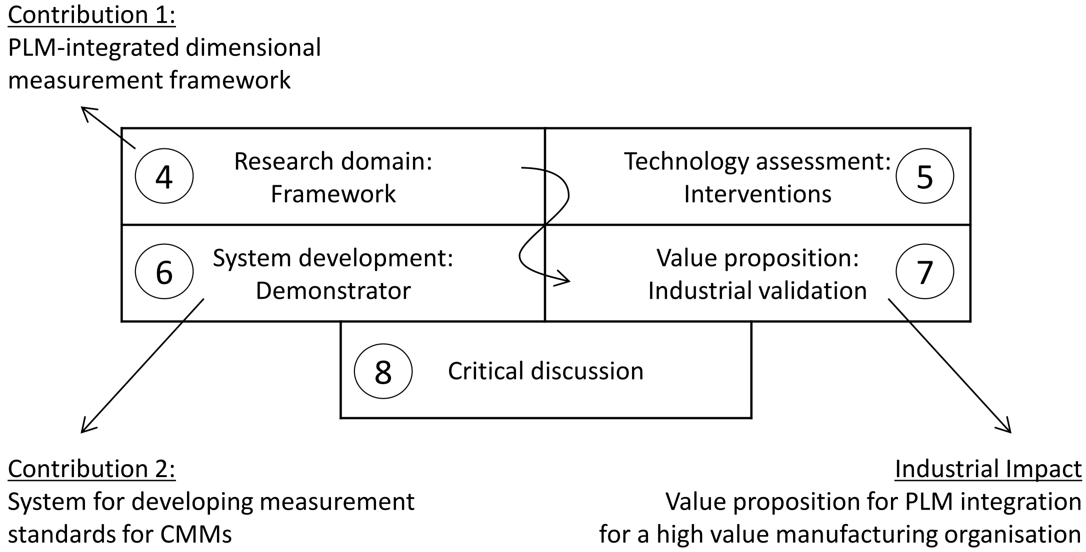


Figure 9-1 Contributions and industrial impact by chapter

9.1.1 Contribution 1: PiDM framework

The first contribution is a research framework labelled 'PLM-integrated dimensional measurement' (PiDM), confronting the fourth gap listed above (refer to Section 2.7.4 for more details). The PiDM framework and associated test cases were developed so that technology solutions could be investigated impartially and systematically. In addition to its use for gap analysis and benchmarking, the framework has improved communication between participating organisations.

The workflow for the framework is grounded on research reported by Evans et al. (2001), later refined by Zhao, Xu, et al. (2011), in which the key processes and interactions for manufacturing measurement were identified. The workflow was updated following interviews with Rolls-Royce representatives, and aspects of these modifications are now reflected in the documentation for the *Quality information framework* (DMSC, 2014b, p. 6). The PLM functional areas were derived from the literature on the purpose of measurement. Thirty-two test cases were developed to validate the approach, and a demonstration was performed of how 'PLM-integrated dimensional measurement' might work in practice using state of art technology.

The PiDM framework has proved to be valuable within this research. Firstly, two commercially available solutions were tested against the framework in Chapter 4; secondly, it was re-employed when formulating the system for developing measurement standards in Chapter 6; thirdly, the framework helped to organise the workflow for the industrial case study in Chapter 7.

The PiDM framework has also been exposed to an international conference (Saunders, Cai, et al., 2013), and stakeholders within the design, manufacturing, and measurement communities at Rolls-Royce plc. In addition it was reviewed by seven other technology users, five technology providers, and four research organisations during its development as part of a core research project at the Manufacturing Technology Centre. At least four of these organisations have now gone on to use it for their own purposes, which have included improving product roadmaps, and applying it in the context of their specific measurement processes and PLM environment.

9.1.2 Contribution 2: System for developing measurement standards for CMMs

The second contribution is a system for developing commodity-specific measurement standards, directly tackling the measurement planning problem for CMMs, and addressing the third gap (Section 2.7.3). It facilitates the selection of competing measurement methods, making use of the capabilities within state of art uncertainty evaluating software (UES) and template-based CMM programming applications. This contribution therefore also goes some way to addressing the gap in the use of predictive measurement uncertainty for CMMs in an industrial setting. (This is the second gap - Section 2.7.2).

The system is based on the National Physical Laboratory's 'scientific approach' (Flack, 2001, pp. 39–42) and builds on the principles of the procedure for uncertainty management (ISO 14253-2, 2011). None of the underlying concepts are new; however, the author believes this to be the first time they have been brought together in a PLM environment to form a comprehensive uncertainty-based measurement planning system.

Novelty is evidenced by the changes which were required in the constituent applications in order to implement and semi-automate the system. For example, in order to facilitate communication between the UES and PLM, the software vendors modified their product so that it could import measurement points and export simulation results. The author then developed scripts within Microsoft Excel® to cleanse and convert data, process the results, and automate the generation of reports. Demonstrations were performed on two component types, and a total of seventeen parts.

The need for a UES-centred approach is supported by four interconnected studies which are documented in Chapter 5. The findings from these studies have been disseminated through two company reports for Rolls-Royce plc, two academic publications (Saunders, Verma, et al., 2013; Saunders, Wilson, et al., 2014), and a presentation to an audience of measurement and process improvement specialists (Saunders, Wilson, et al., 2013). Findings from the development of the system in Chapter 6 were disseminated to member organisations of the Manufacturing Technology Centre who have voted to extend the research; a technical report is in preparation to publicise the results more widely.

9.1.3 Industrial impact: Value proposition for PLM integration for a high value manufacturing organisation

An industrial case study was discussed in Chapter 7. The case study demonstrated the importance that Rolls-Royce plc now place on the topic, which is a shift from the situation prior to this EngD research when the domain was new.

A project has now begun to apply the findings from this EngD on representative Rolls-Royce components (Section 9.4). It is recognised that further research will be required in order to keep up with the pace of change in measurement technology, manufacturing technology, and the means by which design is specified. In addition to providing the data needed to commission the project, the EngD research has been instrumental in the development of an environment in which the project can take place, and has encouraged metrology and PLM vendors to make changes to their products in support of this effort. The project is a pre-requisite to tackling the first gap, which is to identify a common approach for producing and using product and manufacturing information (PMI) (Section 2.7.1).

Recognising that it will be several years before the current project will deliver business benefit, a tactical solution is proposed in Chapter 8. This is an extension to the procedure for uncertainty management (PUMA) (ISO 14253-2, 2011), which can be used as a new way of managing the risk of using methods that do not precisely align to the verification requirements set out in the product definition. This extension to PUMA allows measurement capability data to be fed back to inform verification planning and could potentially influence design processes. Importantly, the procedure respects existing competitive advantages, acknowledging that uncertainty management, at least in the current state of art, requires the input of experts.

9.2 Validation against stakeholder needs

The EngD was commissioned because of the stakeholder's need to reduce 'unmeasurables', which have been defined as features which are costly, or even impossible, to measure when verifying against a specification. The value of the contributions listed in Section 9.1 can be reviewed in the light of how well the EngD met this need, and in particular with respect to the two exploratory case studies which were referenced in Chapter 1.

9.2.1 Improvement to the feature verification risk assessment process

A process known within Rolls-Royce plc as feature verification risk assessment is widely used when introducing products into the manufacturing system (Section 1.4.2 and Section 8.3.1). Each geometric specification is given a score for its design severity (S), manufacturing occurrence (O), and measurement detection (D). The three scores are multiplied together to form a risk priority number and thereby identify features that require attention. Measurement representatives had been found to be at a disadvantage when providing detection scores for this process, because they tended to lack the tools that allowed them to provide defensible numbers.

The research in this EngD has shown how this problem could be addressed by employing uncertainty evaluating software during the feature verification risk assessment process, as indicated at the end of Section 9.1.3. The approach has the benefit of being only an incremental change from current technology and may easily be implemented, thus encouraging technology vendors to invest in developing products in this area for the benefit of all users.

9.2.2 Inclusion of measurement in the robust design optimisation process

A second case study was discussed in Chapter 1 which demonstrated the growing interest that exists within Rolls-Royce plc as to how measurement data can be used by design. In this study, three categories of measurement knowledge were identified in order to improve the relationship with design. The EngD has made a start in nurturing these knowledge types as follows:

- Standardisation of measurement methods

  Standardisation was a key theme in the research. Whilst the focus was on sampling strategy for CMMs in discrete point mode, it is expected that the approach can be extended for other methods and technologies.

- Manufacturing process understanding

  The importance of understanding the manufacturing process, and linking this with standard measurement methods was highlighted. As a result, it is suggested that standards should only be applied where it is known that the manufacturing process is subject to relatively little variation. For Rolls-Royce plc, this would mean creating standards at a factory level initially, before deploying more widely once the impact of manufacturing variation for critical measurement tasks is better understood.

- Novelty

  It was observed that there would be considerable value in capturing the capability of new measurement technology. This was shown to be attainable for existing CMM technology in terms of measurement uncertainty, so it is suggested that the application to new and emerging technology would be a good topic for future research.

Overall, it is the author's judgement that there is a considerable distance to go before design and measurement can be 'joined up' in the manner envisaged in this EngD. Nonetheless, it has been shown that much of the required technology is available and can be brought together to form a system-wide solution. Encouragingly, the stakeholders for this case study which was carried out at the beginning of the research are expected to be key participants in the future work that is continuing beyond this EngD.

9.3 Limitations

The EngD has shown that it is possible to build an uncertainty-based system to develop measurement standards for CMMs using available technology, and that measurement standards could be a crucial link between engineering design and measurement technology. It was observed that such standards are tightly linked with manufacturing processes, and are unlikely to be static. This is one of the reasons why it is proposed that experts are required within the system; judgements need to be made as to when a manufacturing process may change sufficiently to trigger the need to review the measurement standard. However, although much of the technology exists and has been demonstrated during the research, a number of unresolved issues remain.

Firstly, product and manufacturing information (PMI) is not widespread within the aerospace industry, and good practice is not well established. Moreover, updates to PMI standards are being released at a reasonably fast rate, and there are still questions as to how this can be best supported by software.

Secondly, if uncertainty is to be used as a target, it is not clear how this target uncertainty should be derived. Few organisations appear to work to target uncertainties today; indeed, no examples were found within the companies approached during the research. To add to the difficulty, as measurement process owners become more informed about the uncertainty they can achieve, it is anticipated that design engineers will be challenged to justify their targets.

Thirdly, whilst it was shown that uncertainty can be estimated for discrete point measurement, UES needs to be developed further before it can be used with other CMM technologies, such as for scanning, or to use hybrid solutions that employ a mixture of contact and non-contact sensors. Related to this, methods for capturing manufacturing variation should be investigated.

Fourthly, metrology software is fragmented, and despite the efforts of standards organisations, use differing data structures. It is therefore challenging to integrate metrology software within the PLM environment, and the best solution for each vendor is likely to be different.

Finally, it may be undesirable to employ PLM to completely close the loop whereby measurement plans are founded directly from engineering models which are in turn updated based on measurement results. Such an approach could risk duplicating, or even reinforcing, errors. The use of additional independent checks, perhaps by developing the integrity metrics suggested in 6.3.3, could become critical in this environment.

9.4 Future work

The main research question was centred on the feasibility of measurement planning for CMMs in a digital environment. There is no unequivocal answer to this question, since it depends on the complexity of the requirements. However, the research has succeeded in providing sufficient confidence in the technology to secure funding for two new research projects.

The first of these is a continuation of the work at the Manufacturing Technology Centre, in which generic solutions are being developed and the PiDM framework will be enhanced. The second project is a two-year multi-partner research activity which has been initiated by Rolls-Royce plc and is supported by Innovate UK (formerly known as the Technology Strategy Board). The objective of this second project is to create a proof-of-concept demonstration in PLM-integrated dimensional measurement on Rolls-Royce products, with a focus on complex geometry such as aerofoils, the use of advanced alignment techniques and measurement strategies, and integration with several different metrology solutions. This project is also using the PiDM framework at its core.

These two projects will be investigating the limitations highlighted in Section 9.3. However, the author believes that there would be value in addressing topics which lie outside the scope that was set for this EngD. With regard to the constraints listed in Section 1.3, research is needed to challenge the following boundaries:

- High-precision aerospace

  The context within which high-precision aerospace operates provides specific challenges which may be different for other industries. For example, aerospace products tend to have a long life as compared to automotive products. One consequence of this is that measurement systems, once validated, may be changed infrequently. Additionally, the research concentrated on components produced through conventional manufacturing methods. New and emerging technologies and materials were out of scope. The integration of measurement for additive manufacture within PLM, for example, may raise some unique challenges.

- Coordinate measuring machines

  The CMM is currently a dominant technology within high precision manufacturing environments. There are growing numbers of examples where CMMs are being replaced by other measuring techniques. Whilst it is expected that much of the research in this EngD should be extensible, this proposition would need to be tested. There would certainly be new issues to address, such as the management of increasing amounts of data.

- Dimensional metrology

  The scope of the study in this thesis was restricted to dimensional measurement. However, there are other important manufacturing processes which are also isolated from PLM, and might benefit from similar treatment. For example, two areas which were found to be important for Rolls-Royce plc are non-destructive testing and surface engineering.

- Components

  This research was directed at components because it was felt that this is where there would be the maximum impact for the first iteration of PLM integration. Looking at higher-order systems, perhaps beginning with assemblies of mechanical components, would increase complexity to the solution. For example, the supply chain would become more important.

- Manufacturing

  Finally, there is substantial opportunity to extend the research beyond the boundaries of manufacturing, in keeping with the spirit of product lifecycle management. If individual geometric characteristics could be tracked from product development, to manufacturing, to service, and on to repair, it should theoretically be possible to gain significant insight into the performance of products through life, and their relationship to the manufacturing processes which created them.

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Appendix A Supporting dataset for the PIDM framework

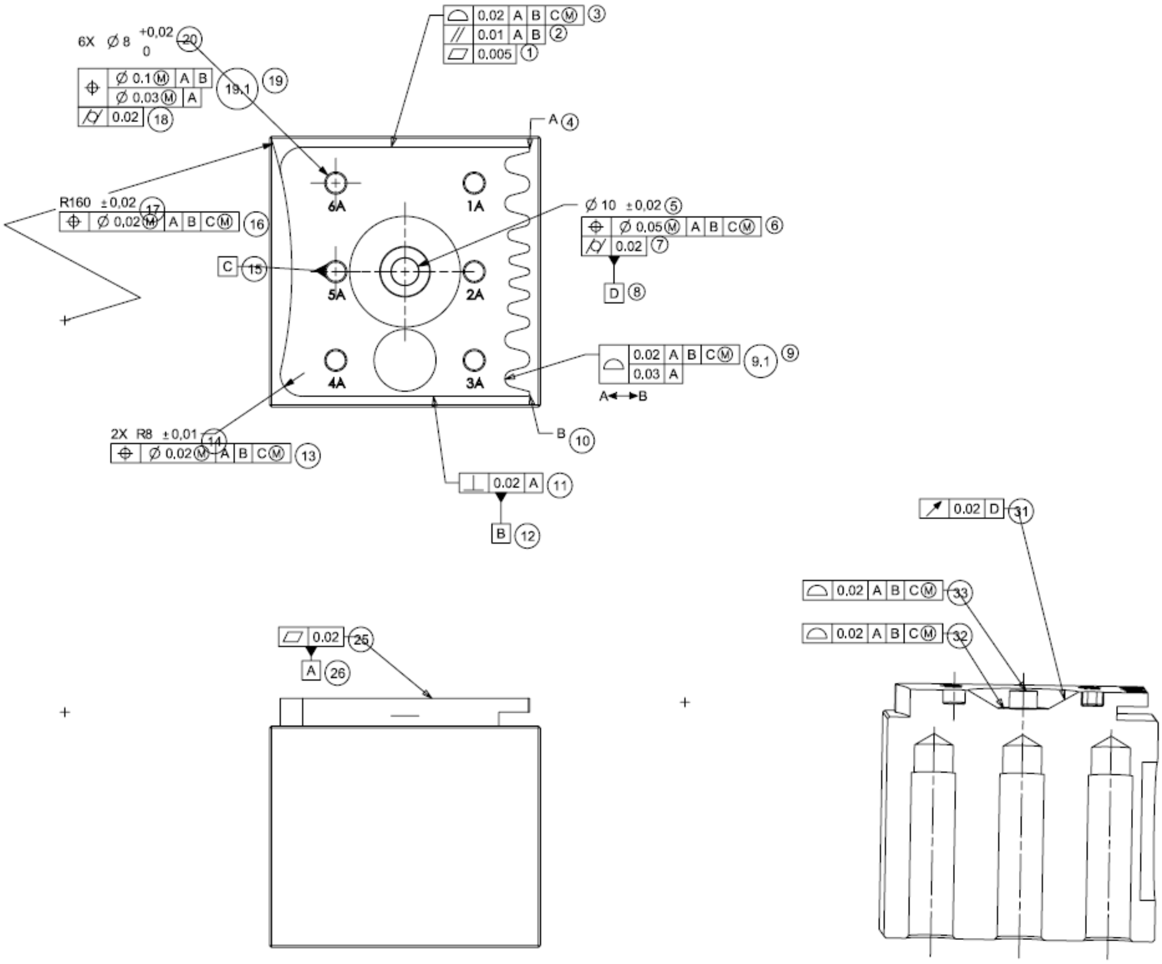

Figure A-1 Block A, showing PMI used for PiDM test cases.[6]

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[6] The PMI shown in this figure is indicative only, reflecting the fact that some of the test cases modified the PMI.

Table A-1 PiDM framework test case summary.

Class	ID	Name	Category	Description
Setup	1.01	partialArc	GD&T Best Practice	Reaction to R8 and R160 partial arcs
PMI Only	2.01	removePMI	Feature: No change / PMI: Remove	Remove callouts 1, 7, 18 (flatness, cylindricity x 2 - note that flatness is a KC)
	2.02	addPMI	Feature: No change / PMI: Add	Add callouts 1, 7, 18 (flatness, cylindricity x 2)
	2.03	modifyProf-Extent	Feature: No change / PMI: Modify	Change the extent of the profile to be measured (9/9.1)
	2.04	modifyProfTol	Feature: No change / PMI: Modify	Change the tolerance value (9.1)
	2.05	modifyProfDat Mod	Feature: No change / PMI: Modify	Remove a datum modifier (9)
	2.06	moveDatum	Feature: No change / PMI: Modify	Move Datum from Hole 5A to 2A (from good to bad)
Feature Only	3.01	removeHole1	Feature: Remove / PMI: No Change	Remove Hole 1A (no PMI assigned to the individual feature, but part of a hole pattern with PMI)
	3.02	addScallop	Feature: Add / PMI: No Change	Add Scallop
	3.03	moveHole	Feature: Modify / PMI: No Change	Move Hole 3A to position of 1A (which has now been removed)
Feature + PMI	4.01	removeHole2	Feature: Remove / PMI: Modify	Remove Hole 2A (now a datum)
	4.02	removeHole6	Feature: Remove / PMI: Modify	Remove Hole 6A (has lots of PMI attached)
	4.03	removeBoss	Feature: Remove / PMI: Remove	Remove Central Boss
	4.04	addBoss	Feature: Add / PMI: Add	Add Central Boss (note: callout 33 will be a KC with a challenging tolerance of, say, 5 µm?)
Simulated	5.01	changeHole-SizeAll	Feature: Modify / PMI: Modify	Change Size of all the holes (reusability test)
	5.02	changeHole-Size4	Feature: Modify / PMI: Modify	Change Size of one of the holes (reusability test)

Class	ID	Name	Category	Description
Measurement Planning	6.01	acquire-Product Geometry	Geometry Import/Export Capability	Determine what common CAD formats exist and which specific formats can be imported/exported
	6.02	acquirePMI	PMI Import/Export Capability	Determine what common PMI formats exist and which specific formats can be imported/exported
	6.03	select-Instruments-Machine	Define a measuring machine	Determine requirements for defining a CMM and limitations
	6.04	select-Instruments-Probe	Define a probe assembly	Determine requirements for building a probe and limitations
	6.05	calibrateProbe	Create program to calibrate required probes	Determine calibration process and implications
	6.06	alignPartTo Machine	Support for alignment methods	Determine what common alignment methods exist and what is supported
	6.07	extract-Features	Define measurement tasks	Define PMI validation method
	6.08	select-Measure-mentStrategy-Reuse	Define methods to reuse measurement strategies	Determine techniques for reusing measurement strategies
	6.09	select-Measure-mentStrategy-Points	Define sampling strategy (distribution, angle, speed, scan path)	What level of control is there over measurement strategies
Measurement Progamming	7.01	generate-Measure-mentPath	Generate measurement path	Determine how to generate the measurement path
	7.02	optimisePath	Optimise path	Identify options for optimisation
	7.03	detect-Collisions	Detect collisions	Explore collision detection strategies
	7.04	avoid-Collisions	Avoid collisions	Explore collision avoidance strategies
	7.05	simulate-Measurement	Simulation of non-nominal geometry	Can the program be fully simulated and can deviations be generated for measured features

Class	ID	Name	Category	Description
Measure-ment Execution	8.01	execute-Program	Execute measurement program	Determine level of interoperability between software and CMMs
Measure-ment Results	9.01	getMeasur-ementResults	Get measurement results	Establish compatibility of the system with different formats

Table A-2 Test case 1.01: partialArc.

1.01	partialArc
Category	GD&T Best Practice
Description	Reaction to R8 and R160 partial arcs
Prerequisites	None
Task Summary	Add R8 and R160 callouts (13, 14, 16, 17)
Data	Not applicable
Resource	Not applicable
V&V	Will the software highlight bad practice with this GD&T assignment?
Feedback	Can the system suggest a better alternative? (e.g. ignore position and inspect as a blend radius, or inspect as a profile)

Table A-3 Test case 2.01: removePMI.

2.01	removePMI
Category	Feature: No change / PMI: Remove
Description	Remove PMI Callouts 1, 7, 18
Prerequisites	Program for part measurement that includes measurement of callouts 1, 7, and 18 (flatnesss and cylindricity of 6 holes + spigot)
Task Summary	Identify flatness callout 1 as a key characteristic Remove flatness callout 1 (a key characteristic) Remove cylindricity callout 7 (boss) Remove cylindricity callout 18 (6 x holes)
Data	How is the history stored? (can you revert back?) How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the PMI changes made by design? What happens to existing PMI ids? (are they changed? Does it depend on the release status of the part?) How do you identify a feature as a key characteristic? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	Does system warn that KC has been removed?
Feedback	N/A

Table A-4 Test case 2.02: addPMI.

2.02	addPMI
Category	Feature: No change / PMI: Add
Description	Add PMI Callouts 1, 7, 18
Prerequisites	Program for part measurement that does not include measurement of callouts 1, 7, and 18 (flatnesss and cylindricity of 6 holes + spigot)
Task Summary	Add flatness callout 1 (a KC) Add cylindricity callout 7 (spigot) Add cylindricity callout 18 (6 x holes)
Data	How is the history stored? (can you revert back?) How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the PMI changes made by design? What happens to existing PMI ids? (are they changed? Does it depend on the release status of the part?) How do you identify a feature as a key characteristic? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert? Will the software warn designer if no suitable measurement resource for a given tolerance? Will the software warn designer if measurement resource will be expensive for a given tolerance?
Feedback	N/A

Table A-5 Test case 2.03: modifyProfExtent.

2.03	modifyProfExtent
Category	Feature: No change / PMI: Modify
Description	Change extent of profile
Prerequisites	Program for part measurement that includes measurement of free-form profile
Task Summary	Move position of 'B' to midpoint of free form profile
Data	How is the history stored? (can you revert back?) Will the measurement planning module see the PMI changes made by design? Does the path change? Does the probe orientation change?
Resource	N/A
V&V	Does software warn that not all of the free form profile has PMI associated with it? (i.e. GD&T is not complete)
Feedback	N/A

Table A-6 Test case 2.04: modifyProfTol.

2.04	modifyProfTol
Category	Feature: No change / PMI: Modify
Description	Change tolerance value for profile
Prerequisites	Program for part measurement that includes measurement of free-form profile
Task Summary	Reduce tolerance of callout 9.1 from 0.03 mm to 0.003 mm
Data	How is the history stored? (can you revert back?) Will the measurement planning module see the PMI changes made by design? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert?
Feedback	Will the software warn designer if no suitable measurement resource for a given tolerance? Will the software warn designer if measurement resource will be expensive for a given tolerance?

Table A-7 Test case 2.05: modifyProfDatMod.

2.05	modifyProfDatMod
Category	Feature: No change / PMI: Modify
Description	Remove datum modifier
Prerequisites	Program for part measurement that includes measurement of free-form profile
Task Summary	Remove datum modifier (M) from callout 9
Data	How is the history stored? (can you revert back?) Will the measurement planning module see the PMI changes made by design? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert?
Feedback	Will the software warn designer if no suitable measurement resource for a given tolerance? Will the software warn designer if measurement resource will be expensive for a given tolerance?

Table A-8 Test case 2.06: moveDatum.

2.06	moveDatum
Category	No change to Feature, Modify PMI
Description	Move Datum C from a 'good' to 'bad' feature
Prerequisites	Program for part measurement that includes measurement of hole 5A, 2A, and all callouts that refer to Datum C
Task Summary	Move Datum C from Hole 5A to 2A
Data	How is the history stored? (can you revert back?) How does the software update the feature library? How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the PMI changes made by design? Does the path change?
Resource	N/A
V&V	Do datums have a different sampling strategy? Is this applied to the new hole?
Feedback	Will the software highlight that the newly selected datum is of a lower quality that the previous datum? (e.g. can you add process capability information against the feature? - or even bring in data obtained from previous measurements?) Will the software highlight affected PMI?

Table A-9 Test Case 3.01: removeHole1.

3.01	removeHole1
Category	Feature: Remove / PMI: No Change
Description	Remove Hole 1A
Prerequisites	Program for part measurement that includes measurement of hole 1A and other holes in the same pattern
Task Summary	Remove hole 1A
Data	How is the history stored? (can you revert back?) How does the software update the feature library? Will the measurement planning module see the feature changes made by design? Does the path change?
Resource	N/A
V&V	N/A
Feedback	N/A

Table A-10 Test case 3.02: addScallop.

3.02	addScallop
Category	Feature: Add / PMI: No Change
Description	Add 'scallop' (i.e. The big depression near the datum B)
Prerequisites	Program for part measurement that includes measurements for checking the flatness callout (25) that are taken where the scallop will be added
Task Summary	Add scallop (no PMI)
Data	How is the history stored? (can you revert back?) How does the software identify the feature? (e.g. does it add a new id?) How can you see the relationship between this feature and other features on the part? Will the measurement planning module see the feature changes made by design? Does the path change? Does the probe orientation change? Does the sampling strategy for checking flatness (25) change to avoid the area now taken up by the scallop
Resource	N/A
V&V	N/A
Feedback	N/A

Table A-11 Test case 3.03: moveHole.

3.03	moveHole
Category	Feature: Modify / PMI: No Change
Description	Move Hole 3A to position of 1A (which has now been removed)
Prerequisites	Program for part measurement that includes measurement 3A, but not 1A
Task Summary	Move Hole 3A to the position of 1A
Data	How is the history stored? (can you revert back?) Will the software maintain the same feature id and product structure? How does the software update the feature library? How can you see the relationship between this feature and other features on the part? Will the measurement planning module see the PMI changes made by design? Does the sampling strategy move with the hole? Does the path change? Does the probe orientation change?
Resource	N/A
V&V	Will the software warn that the measurement program is out of date?
Feedback	N/A

Table A-12 Test case 4.01: removeHole2.

4.01	removeHole2
Category	Feature: Remove / PMI: Modify
Description	Remove Hole 2A (i.e. The new Datum C)
Prerequisites	Program for part measurement that includes measurement of hole 2A and other holes in the same pattern
Task Summary	Remove hole 2A
Data	How is the history stored? (can you revert back?) How does the software update the feature library? How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? Does the path change?
Resource	N/A
V&V	Will the software warn designer that a datum is removed which is referred to in other PMI? Will the software warn designer that the part is no longer fully constrained?
Feedback	Will the software highlight affected PMI?

Table A-13 Test case 4.02: removeHole6.

4.02	removeHole6
Category	Feature: Remove / PMI: Modify
Description	Remove Hole 6A
Prerequisites	Program for part measurement that includes measurement of hole 6A and other holes in the same pattern; also includes PMI for 18, 19, 19.1, and 20
Task Summary	Remove hole 6A
Data	How is the history stored? (can you revert back?) How does the software update the feature library? How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? Does the path change?
Resource	N/A
V&V	Will the software warn designer that PMI is associated with related features, and so needs to be updated
Feedback	Will the software assign the hole pattern PMI to another hole in the pattern?

Table A-14 Test case 4.03: removeBoss.

4.03	removeBoss
Category	Feature: Remove / PMI: Remove
Description	Remove Central Boss
Prerequisites	Program for part measurement with the central spigot is available, including runout tolerance (callout 31), and KC (callout 33)
Task Summary	Remove 10mm diameter boss - to reveal flat bottom of central depression
Data	What happens to callouts 5,6,7,8,31, and 33? How is the history stored? (can you revert back?) How does the software update the feature library? What happens to existing PMI ids? (are they changed? Does it depend on the release status of the part?) Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	Does system warn that KC has been removed? Does system warn that datum has been removed, so 31 can no longer be checked?
Feedback	N/A

Table A-15 Test case 4.04: addBoss.

4.04	addBoss
Category	Feature: Add / PMI: Add
Description	Add Central Boss
Prerequisites	Program for part measurement without the central spigot is available, but does have the central cone to which the spigot will be joined
Task Summary	Add 10mm diameter boss up to height of top plane Add size tolerance as shown in callout 5 (at least one of these PMI callouts will be 'challenging') Add position tolerance as shown in callout 6 Add cylindricity tolerance as shown in callout 7 Add datum D as shown in callout 8 Add runout tolerance as shown in callout 31 Add profile tolerance as shown in callout 33 Identify callout 33 as a key characteristic
Data	How is the history stored? (can you revert back?) How does the software identify the feature? (e.g. does it add a new id?) How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? How do you identify that this is a key characteristic? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert?
Feedback	Will the software warn designer if no suitable measurement resource for a given tolerance? Will the software warn designer if measurement resource will be expensive for a given tolerance?

Table A-16 Test case 5.01: changeHoleSizeAll.

5.01	changeHoleSizeAll
Category	Feature: Modify / PMI: Modify
Description	Change Size of all the holes (reusability test)
Prerequisites	Program for part measurement that includes measurement of all the holes
Task Summary	Change size of all the holes to 20mm (i.e hole 5A and 2A will overlap the cone)
Data	How is the history stored? (can you revert back?) How does the software update the feature library? How can you see the relationship between this feature and other features on the part? Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? Does the path change? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change?
V&V	Will the software warn that the measurement program is out of date? (e.g. for measurement of runout of the cone + cylindricity of the holes)
Feedback	N/A

Table A-17 Test case 5.02: changeHoleSize4.

5.02	changeHoleSize4
Category	Feature: Modify / PMI: Modify
Description	Change Size of one of the holes (reusability test)
Prerequisites	Program for part measurement that includes measurement of all the holes
Task Summary	Change size of Hole 4A from 8 mm to 1 mm Change tolerance of Hole 4A from 0.02 mm to 0.005 mm
Data	How is the history stored? (can you revert back?) How does the software identify the feature? (e.g. does it add a new id?) How does the software update the feature library? How can you see the relationship between this feature and other features on the part? How does the software identify the PMI callouts? (e.g. does it add new ids?) Will the measurement planning module see the feature changes made by design? Will the measurement planning module see the PMI changes made by design? What happens to existing PMI ids? (are they changed? Does it depend on the release status of the part?) How much of the previous program can be reused? Does the probe orientation change?
Resource	Does the measuring system change? Does the probe change due to feature size change?
V&V	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert? Will the software warn designer if no suitable measurement resource for a given tolerance? Will the software warn designer if measurement resource will be expensive for a given tolerance?
Feedback	Does the path change?

Table A-18 Test case 6.01: acquireProductGeometry.

6.01	acquireProductGeometry
Category	Measurement Planning Tests
Description	Geometry Import/Export Capability
Prerequisites	CAD model
Task Summary	Determine what common CAD formats exist and which specific formats can be imported/exported Document formats in tabular form

Table A-19 Test case 6.02: acquirePMI.

6.02	acquirePMI
Category	Measurement Planning Tests
Description	PMI Import/Export Capability
Prerequisites	CAD model + PMI (Siemens and PC-DMIS)
Task Summary	Determine what PMI formats can be imported/exported from Siemens and PC-DMIS Use PC-DMIS to import PMI from Siemens Use Siemens to import PMI from PC-DMIS

Table A-20 Test case 6.03: selectInstrumentsMachine.

6.03	selectInstrumentsMachine
Category	Measurement Planning Tests
Description	Define a measuring machine
Prerequisites	CAD model for artefact and machine
Task Summary	Determine requirements for defining a CMM and limitations Document requirements for defining a CMM in PC-DMIS Document requirements for defining a CMM in Siemens

Table A-21 Test case 6.04: selectInstrumentsProbe.

6.04	selectInstrumentsProbe
Category	Measurement Planning Tests
Description	Define a probe assembly
Prerequisites	CAD model for artefact and probe assembly
Task Summary	Determine requirements for building a probe and limitations Use PC-DMIS to define the probes that will be used in physical testing Use Siemens to define the probes that will be used in physical testing

Table A-22 Test case 6.05: calibrateProbe.

6.05	calibrateProbe
Category	Measurement Planning Tests
Description	Create program to calibrate required probes
Prerequisites	Probes are defined
Task Summary	Determine calibration process and implications Document formats in tabular form
Questions	Can Siemens Inspector read angles from NX, and is NX aware of calibrated probes / process? How does calibration data flow between execution and programming modules

Table A-23 Test case 6.06: alignPartToMachine.

6.06	alignPartToMachine
Category	Measurement Planning Tests
Description	Support for alignment methods
Prerequisites	Defined machine and imported CAD geometry
Task Summary	Determine what common alignment methods exist and what is supported
	Document alignment methods in tabular form
	Switch between manual, 3-2-1, and iterative

Table A-24 Test case 6.07: extractFeatures.

6.07	extractFeatures
Category	Measurement Planning Tests
Description	Define measurement tasks
Prerequisites	CAD model + PMI
Task Summary	Define PMI validation method
Questions	How do you ignore PMI?
	Are there ways of communicating measurement objectives? (e.g. attributes of PMI that state reduced inspection is allowed)
	How does the software apply the GD&T standards?

Table A-25 Test case 6.08: selectMeasurementStrategy-Reuse.

6.08	selectMeasurementStrategy-Reuse
Category	Measurement Planning Tests
Description	Define methods to reuse measurement strategies
Prerequisites	CAD model + PMI + extracted features + pre-existing strategies to reuse
Task Summary	Determine techniques for reusing measurement strategies
	Document available reuse strategies in Siemens
	Document available reuse strategies in PC-DMIS

Table A-26 Test case 6.09: selectMeasurementStrategy-Points.

6.09	selectMeasurementStrategy-Points
Category	Measurement Planning Tests
Description	Define sampling strategy (distribution, angle, speed, scan path)
Prerequisites	CAD model + PMI + extracted features
Task Summary	Identify what level of control there is over point distribution Identify what level of control there is over probe angles Identify what level of control there is over probe speeds Identify what level of control there is over path scanning Automatically generate probe angles when given full flexibility (ignoring optimisation)
Questions	Can the point distribution strategies in ISO 14406 (2010) / BS 7172(1989) be followed? Are there any standards for path scanning? (e.g. for Revo) What are the differences between the Siemens and PC-DMIS approach? In Siemens, is there a difference between the path Revo and discrete point measurement? How do you implement reduced inspection strategies? How do you implement the scientific approach to point distribution in BPG41 Section 8.2.2

Table A-27 Test case 7.01: generateMeasurementPath.

7.01	generateMeasurementPath
Category	Measurement Programming Tests
Description	Generate measurement path
Prerequisites	Machine, probe + defined sampling strategy for all features
Task Summary	Take a screenshot of the paths from each system

Table A-28 Test case 7.02: optimisePath.

7.02	optimisePath
Category	Measurement Programming Tests
Description	Optimise path
Prerequisites	Machine, probe + defined sampling strategy for all features + generated paths
Task Summary	Document optimisation method in each system
Questions	What level of optimisation is available? Feature by feature or Totality of measurement?

Table A-29 Test case 7.03: detectCollisions.

7.03	detectCollisions
Category	Measurement Programming Tests
Description	Detect collisions
Prerequisites	Machine, probe + defined sampling strategy for all features + generated paths
Task Summary	Document collision detection method in each system
Questions	When does collision detection occur? What detection modes can you select? (pairs/all)

Table A-30 Test case 7.04: avoidCollisions.

7.04	avoidCollisions
Category	Measurement Programming Tests
Description	Avoid collisions
Prerequisites	Machine, probe + defined sampling strategy for all features + paths with collisions
Task Summary	Generate a table Compare out-of-box with best practice, as supported by Vendors
Questions	What strategies are employed to avoid collisions? How effective are they? (demo video)

Table A-31 Test case 7.05: simulateMeasurement.

7.05	simulateMeasurement
Category	Measurement Programming Tests
Description	Simulation of non-nominal geometry
Prerequisites	Machine, probe + defined sampling strategy for all features + generated paths
Task Summary	Explore options for simulation
Questions	Can the program be fully simulated and can deviations be generated for measured features?

Table A-32 Test case 8.01: executeProgram.

8.01	executeProgram
Category	Measurement Execution Tests
Description	Execute measurement program
Prerequisites	CMM Program (I++)
Task Summary	Document supported format / machines / controllers
Questions	How interoperable is the solution?

Table A-33 Test case 9.01: getMeasurementResults.

9.01	getMeasurementResults
Category	Measurement Results Tests
Description	Get measurement results
Prerequisites	Measurement results
Task Summary	Document supported formats?
Questions	Can results be associated back to the model?

Table A-34 Summary of test case questions.

ID	Question	Category
1.01	Will the software highlight bad practice with this GD&T assignment?	V&V
1.01	Can the system suggest a better alternative? (e.g. ignore position and inspect as a blend radius, or inspect as a profile)	Feedback
2.01	Does the probe orientation change?	Data
2.01	Does the path change?	Data
2.01	Will the measurement planning module see the PMI changes made by design?	Data
2.01	How do you identify a feature as a key characteristic?	Data
2.01	Does system warn that KC has been removed?	V&V
2.01	Does the measuring system change?	Resource
2.01	Does the probe change?	Resource
2.01	How is the history stored? (can you revert back?)	Data
2.01	How does the software identify the PMI callouts? (e.g. does it add new ids?)	Data
2.01	What happens to existing PMI ids? (are they changed? Does it depend on the release status of the part?)	Data
2.02	How can one know that the sampling strategy is appropriate? (e.g. if very tight tolerance, or poor form expected) E.g if PMI cannot be reasonably assessed with preselected probe, will the software raise an alert?	V&V
2.02	Will the software warn designer if no suitable measurement resource for a given tolerance?	V&V
2.02	Will the software warn designer if measurement resource will be expensive for a given tolerance?	V&V
2.03	Does software warn that not all of the free form profile has PMI associated with it? (i.e. GD&T is not complete)	V&V
2.06	Do datums have a different sampling strategy? Is this applied to the new hole?	V&V
2.06	Will the software highlight affected PMI?	Feedback
2.06	Will the software highlight that the newly selected datum is of a lower quality that the previous datum? (e.g. can you add process capability information against the feature? - or even bring in data obtained from previous measurements?)	Feedback
2.06	How does the software update the feature library?	Data

ID	Question	Category
2.06	How can you see the relationship between this feature and other features on the part?	Data
3.02	Does the sampling strategy for checking flatness (25) change to avoid the area now taken up by the scallop	Data
3.03	Will the software warn that the measurement program is out of date?	V&V
3.03	Will the software maintain the same feature id and product structure?	Data
3.03	Does the sampling strategy move with the hole?	Data
4.01	Will the software warn designer that the part is no longer fully constrained?	V&V
4.01	Will the software warn designer that a datum is removed which is referred to in other PMI?	V&V
4.02	Will the software warn designer that PMI is associated with related features, and so needs to be updated	V&V
4.02	Will the software assign the hole pattern PMI to another hole in the pattern?	Feedback
4.03	Does system warn that datum has been removed, so 31 can no longer be checked?	V&V
4.03	What happens to callouts 5,6,7,8,31, and 33?	Data
5.02	Does the probe change due to feature size change?	Resource
5.02	How much of the previous program can be reused?	Data
6.05	Can Siemens Inspector read angles from NX, and is NX aware of calibrated probes / process?	Process
6.05	How does calibration data flow between execution and programming modules	Process
6.07	How do you ignore PMI?	Process
6.07	Are there ways of communicating measurement objectives through PMI?	Process
6.07	How does the software apply the GD&T standards?	Process
6.09	Can the point distribution strategies in ISO 14406 (2010) / BS 7172(1989) be followed?	Process
6.09	Are there any standards for path scanning?	Process
6.09	What are the differences between the Siemens and PC-DMIS approach?	Process
6.09	In Siemens, is there a difference between the path Revo and discrete point measurement?	Process
6.09	How do you implement reduced inspection strategies?	Process
6.09	How do you implement the scientific approach to point distribution in BPG41 Section 8.2.2	Process
7.02	What level of optimisation is available?	Process
7.02	Feature by feature or Totality of measurement?	Process
7.03	When does collision detection occur?	Process
7.03	What detection modes can you select? (pairs/all)	Process
7.04	What strategies are employed to avoid collisions?	Process
7.04	How effective are they? (demo video)	Process

ID	Question	Category
7.05	Can the program be fully simulated and can deviations be generated for measured features?	Process
8.01	How interoperable is the solution?	Process
9.01	Can results be associated back to the model?	Process

Appendix B Supporting dataset for the measurement standard system

B.1 Measuring system characteristics

Table B-1 Measuring system description used for uncertainty simulation.

Parameter	CMM A	CMM B	CMM C
CMM make and model	Leitz PMM-C 12.10.7	Nikon L.K.V. 15.12.10	Nikon L.K.V. 30.20.20
Probe head make and model	Leitz LSP-X1c	Renishaw PH10M / SP25	Renishaw REVO
CMM type	Fixed bridge	Moving bridge	Moving bridge
CMM extents	X: 0 to 1200 mm Y: 0 to 1000 mm Z: 0 to 700 mm	X: 0 to 1217 mm Y: 0 to 1541 mm Z: 0 to 1030 mm	X: 0 to 2015 mm Y: 0 to 3020 mm Z: 0 to 1408 mm
CMM orientation	X=+A; Y=+B; Z=+C	X=+A; Y=+B; Z=+C	X=+A; Y=+B; Z=+C
Scale type	Standard (not laser)	Standard (not laser)	Standard (not laser)
Coefficient of expansion	0 ppm / ^{0}C	11.8 ppm / ^{0}C	11.8 ppm / ^{0}C
Uncertainty of coefficient	0 ppm / ^{0}C	1.2 ppm / ^{0}C	1.2 ppm / ^{0}C
Temperature	20 ^{0}C	20 ^{0}C	20 ^{0}C
Uncertainty of temperature	1 ^{0}C	1 ^{0}C	1 ^{0}C
Temperature compensation	None	None	None
ISO 10360 Error of Indication	E = ± 0.0006 mm + 0.0017 mm × [L(mm)/1000mm]	E = ± 0.0019 mm + 0.0027 mm × [L(mm)/1000mm]	E = ± 0.003 mm + 0.0025 mm × [L(mm)/1000mm]
ISO 10360 method	Gauge blocks	Gauge blocks	Gauge blocks
Sensor type	Fixed orientation Single tip	Fixed orientation Single tip	Fixed orientation Single tip
Sensor trigger technology	Switching probe	Switching probe	Switching probe
ISO 10360 range of residuals to 25-point sphere fit	0.0002 mm	0.00092 mm	0.002 mm
ISO 10360 stylus length in test	80 mm	21 mm	80 mm
Stylus tip orientation	-Z CMM axis	-Z CMM axis	-Z CMM axis
Stylus length	50 mm	50 mm	50 mm

B.2 CTC 1: Rolls-Royce multi-feature artefact

Table B-2 Range of measured values, scenario 1, CMM A, CTC 1.

Scenario 1 – Range of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Size	Hole 1A	0.0010	0.0011	0.0011	0.0011
	Hole 2A	0.0014	0.0011	0.0010	0.0011
	Hole 3A	0.0009	0.0009	0.0011	0.0009
	Hole 4A	0.0009	0.0009	0.0010	0.0009
	Hole 5A	0.0014	0.0007	0.0008	0.0006
	Hole 6A	0.0013	0.0009	0.0010	0.0008
	Central Boss	0.0013	0.0009	0.0012	0.0011
Position (ABC)	Hole 1A	0.0017	0.0017	0.0017	0.0016
	Hole 2A	0.0011	0.0013	0.0006	0.0008
	Hole 3A	0.0021	0.0060	0.0040	0.0039
	Hole 4A	0.0031	0.0025	0.0026	0.0026
	Hole 6A	0.0012	0.0015	0.0011	0.0012
	Central Boss	0.0027	0.0021	0.0021	0.0022
Cylindricity	Hole 1A	0.0005	0.0004	0.0007	0.0006
	Hole 2A	0.0004	0.0003	0.0005	0.0003
	Hole 3A	0.0003	0.0005	0.0003	0.0007
	Hole 4A	0.0001	0.0004	0.0003	0.0004
	Hole 5A	0.0004	0.0002	0.0013	0.0031
	Hole 6A	0.0082	0.0002	0.0009	0.0084
	Central Boss	0.0004	0.0002	0.0003	0.0001
Run-out (to D)	Cone	0.0051	0.0092	0.0095	0.0089
Flatness	Datum A	0.0000	0.0002	0.0000	0.0000
	Non-datum plane	0.0003	0.0003	0.0000	0.0004
Perp (to A)	Datum B	0.0004	0.0004	0.0004	0.0004
Prof (to ABC)	Non-datum plane	0.0013	0.0013	0.0012	0.0013
Parallel (to B)	Non-datum plane	0.0009	0.0009	0.0009	0.0008

Table B-3 Average of measured values, scenario 1, CMM A, CTC 1.

Scenario 1 – Average of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Size	Hole 1A	7.9860	7.9862	7.9858	7.9861
	Hole 2A	8.0011	7.9886	7.9878	7.9879
	Hole 3A	7.9848	8.0057	7.9899	7.9907
	Hole 4A	7.9903	8.0042	7.9921	7.9928
	Hole 5A	7.9972	7.9975	7.9972	7.9974
	Hole 6A	8.0101	8.0102	8.0103	8.0103
	Central Boss	10.0039	10.0020	10.0009	10.0018
Position (ABC)	Hole 1A	0.0327	0.0134	0.0119	0.0108
	Hole 2A	0.0036	0.0350	0.0084	0.0089
	Hole 3A	0.0218	0.0042	0.0059	0.0071
	Hole 4A	0.0399	0.0393	0.0263	0.0260
	Hole 6A	0.0071	0.0091	0.0086	0.0085
	Central Boss	0.0611	0.0238	0.0199	0.0203
Cylindricity	Hole 1A	0.0054	0.0217	0.0294	0.0331
	Hole 2A	0.0037	0.0078	0.0311	0.0357
	Hole 3A	0.0023	0.0041	0.0295	0.0346
	Hole 4A	0.0030	0.0125	0.0334	0.0353
	Hole 5A	0.0007	0.0019	0.0028	0.0041
	Hole 6A	0.0025	0.0014	0.0021	0.0046
	Central Boss	0.0149	0.0415	0.0532	0.0564
Run-out (to D)	Cone	0.0056	0.0068	0.0075	0.0080
Flatness	Datum A	0.0007	0.0008	0.0009	0.0090
	Non-datum plane	0.0008	0.0013	0.0016	0.0022
Perp (to A)	Datum B	0.0036	0.0036	0.0036	0.0036
Prof (to ABC)	Non-datum plane	0.0031	0.0032	0.0034	0.0042
Parallel (to B)	Non-datum plane	0.0039	0.0040	0.0039	0.0054

Table B-4 Range of measured values, scenario 1, CMM B, CTC 1.

Scenario 1 – Range of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Size	Hole 1A	0.0019	0.0025	0.0018	0.0020
	Hole 2A	0.0014	0.0015	**0.0043**	0.0016
	Hole 3A	0.0018	0.0012	0.0012	0.0015
	Hole 4A	0.0012	0.0049	0.0012	0.0013
	Hole 5A	0.0010	0.0012	0.0013	0.0011
	Hole 6A	0.0014	0.0018	0.0017	0.0017
	Central Boss	0.0014	0.0012	0.0012	0.0012
Position (ABC)	Hole 1A	0.0127	0.0074	0.0075	0.0060
	Hole 2A	0.0085	0.0070	0.0030	0.0019
	Hole 3A	0.0121	0.0085	0.0090	0.0112
	Hole 4A	0.0107	0.0084	0.0081	0.0081
	Hole 6A	0.0033	0.0040	0.0034	0.0033
	Central Boss	0.0103	0.0050	0.0039	0.0046
Cylindricity	Hole 1A	0.0012	0.0022	0.0002	0.0016
	Hole 2A	0.0016	0.0012	0.0008	0.0004
	Hole 3A	0.0012	0.0006	0.0004	0.0006
	Hole 4A	0.0001	0.0237	0.0006	0.0054
	Hole 5A	0.0012	0.0009	0.0032	0.0022
	Hole 6A	0.0005	0.0003	0.0006	0.0018
	Central Boss	0.0007	0.0007	0.0005	0.0004
Run-out (to D)	Cone	0.0089	0.0103	0.0112	0.0113
Flatness	Datum A	0.0003	0.0003	0.0003	0.0004
	Non-datum plane	0.0007	0.0004	0.0004	0.0002
Perp (to A)	Datum B	0.0028	0.0029	0.0029	0.0029
Prof (to ABC)	Non-datum plane	0.0022	0.0021	0.0026	0.0019
Parallel (to B)	Non-datum plane	0.0060	0.0057	0.0058	0.0051

Table B-5 Average of measured values, scenario 1, CMM B, CTC 1.

Scenario 1 – Average of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Size	Hole 1A	7.9840	7.9843	7.9837	7.9842
	Hole 2A	7.9996	7.9870	7.9854	7.9863
	Hole 3A	7.9829	8.0040	7.9882	7.9889
	Hole 4A	7.9884	8.0016	7.9903	7.9910
	Hole 5A	7.9955	7.9961	7.9957	7.9960
	Hole 6A	8.0084	8.0086	8.0087	8.0087
	Central Boss	10.0056	10.0040	10.0029	10.0037
Position (ABC)	Hole 1A	0.0261	0.0091	0.0082	0.0076
	Hole 2A	0.0082	0.0289	0.0053	0.0055
	Hole 3A	0.0266	0.0090	0.0062	0.0075
	Hole 4A	0.0363	0.0342	0.0220	0.0221
	Hole 6A	0.0074	0.0093	0.0082	0.0081
	Central Boss	0.0554	0.0192	0.0155	0.0158
Cylindricity	Hole 1A	0.0045	0.0228	0.0296	0.0338
	Hole 2A	0.0028	0.0074	0.0309	0.0358
	Hole 3A	0.0016	0.0040	0.0296	0.0343
	Hole 4A	0.0029	0.0179	0.0338	0.0371
	Hole 5A	0.0015	0.0020	0.0043	0.0050
	Hole 6A	0.0012	0.0017	0.0025	0.0039
	Central Boss	0.0159	0.0410	0.0533	0.0564
Run-out (to D)	Cone	0.0062	0.0069	0.0076	0.0086
Flatness	Datum A	0.0005	0.0007	0.0007	0.0090
	Non-datum plane	0.0011	0.0014	0.0016	0.0024
Perp (to A)	Datum B	0.0041	0.0041	0.0041	0.0041
Prof (to ABC)	Non-datum plane	0.0034	0.0035	0.0037	0.0041
Parallel (to B)	Non-datum plane	0.0057	0.0058	0.0058	0.0064

Table B-6 Range of measured values, scenario 2, CMM A, CTC 1.

Scenario 2 – Range of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Position (ABC)	Hole 1A	0.0016	0.0016	0.0015	0.0016
	Hole 2A	0.0008	0.0008	0.0008	0.0008
	Hole 3A	0.0035	0.0038	0.0038	0.0039
	Hole 4A	0.0026	0.0023	0.0024	0.0026
	Hole 6A	0.0008	0.0015	0.0013	0.0012
	Central Boss	0.0019	0.0018	0.0020	0.0022
Position (ABE)	Hole 2A	0.0006	0.0010	0.0010	0.0010
	Hole 3A	0.0019	0.0033	0.0034	0.0035
	Hole 4A	0.0018	0.0023	0.0023	0.0025
	Hole 5A	0.0015	0.0029	0.0030	0.0031
	Hole 6A	0.0011	0.0012	0.0011	0.0010
	Central Boss	0.0015	0.0021	0.0021	0.0022
Position (ABF)	Hole 1A	0.0017	0.0014	0.0013	0.0011
	Hole 3A	0.0029	0.0011	0.0034	0.0037
	Hole 4A	0.0024	0.0014	0.0022	0.0022
	Hole 5A	0.0022	0.0019	0.0029	0.0028
	Hole 6A	0.0013	0.0021	0.0014	0.0017
	Central Boss	0.0018	0.0014	0.0020	0.0022
Position (ABG)	Hole 1A	0.0014	0.0015	0.0013	0.0013
	Hole 2A	0.0009	0.0010	0.0006	0.0007
	Hole 4A	0.0022	0.0025	0.0025	0.0026
	Hole 5A	0.0018	0.0028	0.0029	0.0027
	Hole 6A	0.0022	0.0014	0.0016	0.0019
	Central Boss	0.0018	0.0020	0.0021	0.0022
Position (ABH)	Hole 1A	0.0016	0.0014	0.0014	0.0016
	Hole 2A	0.0006	0.0019	0.0020	0.0020
	Hole 3A	0.0037	0.0037	0.0036	0.0037
	Hole 5A	0.0022	0.0031	0.0028	0.0030
	Hole 6A	0.0012	0.0010	0.0010	0.0009
	Central Boss	0.0017	0.0025	0.0024	0.0027
Run-out (to D)	Cone	0.0143	0.0218	0.0106	0.0089
Perp (to A)	Datum B	0.0004	0.0004	0.0004	0.0004
Prof (to ABC)	Non-datum plane	0.0013	0.0012	0.0012	0.0013
Prof (to ABE)	Non-datum plane	0.0013	0.0012	0.0012	0.0013
Prof (to ABF)	Non-datum plane	0.0013	0.0012	0.0012	0.0013
Prof (to ABG)	Non-datum plane	0.0013	0.0012	0.0012	0.0013
Prof (to ABH)	Non-datum plane	0.0013	0.0012	0.0012	0.0013
Parallel (to B)	Non-datum plane	0.0008	0.0007	0.0007	0.0009

Table B-7 Average of measured values, scenario 2, CMM A, CTC 1.

Scenario 2 – Average of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Position (ABC)	Hole 1A	0.0118	0.0114	0.0115	0.0108
	Hole 2A	0.0097	0.0093	0.0095	0.0089
	Hole 3A	0.0076	0.0073	0.0076	0.0071
	Hole 4A	0.0269	0.0266	0.0267	0.0260
	Hole 6A	0.0093	0.0090	0.0090	0.0085
	Central Boss	0.0211	0.0208	0.0209	0.0203
Position (ABE)	Hole 2A	0.0121	0.0101	0.0102	0.0094
	Hole 3A	0.0089	0.0091	0.0092	0.0085
	Hole 4A	0.0309	0.0255	0.0257	0.0252
	Hole 5A	0.0121	0.0082	0.0083	0.0077
	Hole 6A	0.0149	0.0079	0.0080	0.0076
	Central Boss	0.0231	0.0208	0.0209	0.0203
Position (ABF)	Hole 1A	0.0121	0.0199	0.0115	0.0112
	Hole 3A	0.0111	0.0132	0.0077	0.0065
	Hole 4A	0.0251	0.0348	0.0266	0.0266
	Hole 5A	0.0094	0.0172	0.0080	0.0077
	Hole 6A	0.0081	0.0205	0.0089	0.0093
	Central Boss	0.0214	0.0261	0.0209	0.0204
Position (ABG)	Hole 1A	0.0176	0.0112	0.0118	0.0118
	Hole 2A	0.0143	0.0095	0.0095	0.0091
	Hole 4A	0.0328	0.0261	0.0272	0.0274
	Hole 5A	0.0146	0.0079	0.0082	0.0083
	Hole 6A	0.0176	0.0085	0.0097	0.0105
	Central Boss	0.0246	0.0207	0.0211	0.0207
Position (ABH)	Hole 1A	0.0120	0.0136	0.0146	0.0133
	Hole 2A	0.0097	0.0141	0.0153	0.0139
	Hole 3A	0.0073	0.0146	0.0159	0.0146
	Hole 5A	0.0084	0.0120	0.0131	0.0119
	Hole 6A	0.0098	0.0094	0.0104	0.0091
	Central Boss	0.0212	0.0223	0.0231	0.0220
Run-out (to D)	Cone	0.0334	0.0170	0.0215	0.0080
Perp (to A)	Datum B	0.0036	0.0036	0.0036	0.0036
Prof (to ABC)	Non-datum plane	0.0045	0.0043	0.0044	0.0042
Prof (to ABE)	Non-datum plane	0.0045	0.0043	0.0044	0.0042
Prof (to ABF)	Non-datum plane	0.0045	0.0043	0.0044	0.0042
Prof (to ABG)	Non-datum plane	0.0045	0.0043	0.0044	0.0042
Prof (to ABH)	Non-datum plane	0.0045	0.0043	0.0044	0.0042
Parallel (to B)	Non-datum plane	0.0042	0.0042	0.0048	0.0052

Table B-8 Range of measured values, scenario 2, CMM B, CTC 1.

Scenario 2 – Range of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Position (ABC)	Hole 1A	0.0068	0.0064	0.0067	0.0060
	Hole 2A	0.0016	0.0017	0.0021	0.0019
	Hole 3A	0.0097	0.0103	0.0099	0.0112
	Hole 4A	0.0087	0.0085	0.0085	0.0081
	Hole 6A	0.0029	0.0030	0.0034	0.0033
	Central Boss	0.0049	0.0048	0.0047	0.0046
Position (ABE)	Hole 2A	0.0090	0.0067	0.0068	0.0067
	Hole 3A	0.0049	0.0129	0.0122	0.0132
	Hole 4A	0.0058	0.0088	0.0087	0.0083
	Hole 5A	0.0050	0.0071	0.0066	0.0070
	Hole 6A	0.0042	0.0056	0.0058	0.0060
	Central Boss	0.0021	0.0074	0.0074	0.0070
Position (ABF)	Hole 1A	0.0108	0.0054	0.0058	0.0044
	Hole 3A	0.0062	0.0042	0.0054	0.0054
	Hole 4A	0.0074	0.0016	0.0054	0.0044
	Hole 5A	0.0013	0.0031	0.0028	0.0036
	Hole 6A	0.0072	0.0103	0.0072	0.0075
	Central Boss	0.0069	0.0056	0.0031	0.0016
Position (ABG)	Hole 1A	0.0091	0.0041	0.0046	0.0061
	Hole 2A	0.0010	0.0032	0.0019	0.0015
	Hole 4A	0.0041	0.0033	0.0030	0.0027
	Hole 5A	0.0058	0.0051	0.0061	0.0068
	Hole 6A	0.0143	0.0096	0.0117	0.0136
	Central Boss	0.0090	0.0016	0.0031	0.0049
Position (ABH)	Hole 1A	0.0053	0.0099	0.0100	0.0102
	Hole 2A	0.0049	0.0077	0.0080	0.0077
	Hole 3A	0.0070	0.0104	0.0110	0.0109
	Hole 5A	0.0033	0.0060	0.0069	0.0067
	Hole 6A	0.0043	0.0071	0.0089	0.0076
	Central Boss	0.0040	0.0083	0.0089	0.0087
Run-out (to D)	Cone	0.0204	0.0323	0.0313	0.0113
Perp (to A)	Datum B	0.0028	0.0029	0.0029	0.0029
Prof (to ABC)	Non-datum plane	0.0015	0.0016	0.0016	0.0019
Prof (to ABE)	Non-datum plane	0.0015	0.0016	0.0016	0.0019
Prof (to ABF)	Non-datum plane	0.0015	0.0016	0.0016	0.0019
Prof (to ABG)	Non-datum plane	0.0015	0.0016	0.0016	0.0019
Prof (to ABH)	Non-datum plane	0.0015	0.0016	0.0016	0.0019
Parallel (to B)	Non-datum plane	0.0046	0.0047	0.0049	0.0051

Table B-9 Average of measured values, scenario 2, CMM B, CTC 1.

Scenario 2 – Average of measured values from 5 runs (mm)					
PMI Type	Feature	Low	Med	High	Ref
Position (ABC)	Hole 1A	0.0082	0.0079	0.0080	0.0079
	Hole 2A	0.0059	0.0056	0.0057	0.0056
	Hole 3A	0.0077	0.0077	0.0078	0.0076
	Hole 4A	0.0230	0.0227	0.0227	0.0221
	Hole 6A	0.0086	0.0084	0.0084	0.0081
	Central Boss	0.0166	0.0163	0.0165	0.0160
Position (ABE)	Hole 2A	0.0066	0.0084	0.0084	0.0080
	Hole 3A	0.0063	0.0130	0.0130	0.0126
	Hole 4A	0.0252	0.0214	0.0215	0.0209
	Hole 5A	0.0067	0.0070	0.0069	0.0064
	Hole 6A	0.0124	0.0040	0.0040	0.0036
	Central Boss	0.0182	0.0162	0.0163	0.0156
Position (ABF)	Hole 1A	0.0062	0.0196	0.0080	0.0085
	Hole 3A	0.0126	0.0087	0.0081	0.0067
	Hole 4A	0.0216	0.0304	0.0226	0.0225
	Hole 5A	0.0067	0.0146	0.0038	0.0034
	Hole 6A	0.0053	0.0210	0.0081	0.0090
	Central Boss	0.0167	0.0234	0.0167	0.0164
Position (ABG)	Hole 1A	0.0210	0.0104	0.0123	0.0133
	Hole 2A	0.0151	0.0045	0.0061	0.0071
	Hole 4A	0.0316	0.0238	0.0251	0.0254
	Hole 5A	0.0159	0.0048	0.0064	0.0074
	Hole 6A	0.0222	0.0109	0.0129	0.0141
	Central Boss	0.0247	0.0177	0.0187	0.0189
Position (ABH)	Hole 1A	0.0109	0.0062	0.0072	0.0060
	Hole 2A	0.0061	0.0092	0.0105	0.0092
	Hole 3A	0.0056	0.0143	0.0156	0.0144
	Hole 5A	0.0062	0.0079	0.0092	0.0079
	Hole 6A	0.0118	0.0047	0.0050	0.0045
	Central Boss	0.0177	0.0164	0.0169	0.0159
Run-out (to D)	Cone	0.0357	0.0189	0.0210	0.0086
Perp (to A)	Datum B	0.0041	0.0041	0.0041	0.0041
Prof (to ABC)	Non-datum plane	0.0038	0.0039	0.0039	0.0041
Prof (to ABE)	Non-datum plane	0.0038	0.0039	0.0039	0.0041
Prof (to ABF)	Non-datum plane	0.0038	0.0039	0.0039	0.0041
Prof (to ABG)	Non-datum plane	0.0038	0.0039	0.0039	0.0041
Prof (to ABH)	Non-datum plane	0.0038	0.0039	0.0039	0.0041
Parallel (to B)	Non-datum plane	0.0054	0.0055	0.0061	0.0064

Table B-10 Software inter-comparison, scenario 1, CMM A, run 1, low, CTC 1.

		Software package				
PMI Type	Feature	A	B	C	D	E
Size	Hole 1A	7.9866	7.9866	7.9866	7.9866	7.9820
	Hole 2A	8.0020	8.0020	8.0020	8.0019	7.9986
	Hole 3A	7.9855	7.9855	7.9855	7.9854	7.9835
	Hole 4A	7.9908	7.9908	7.9908	7.9908	7.9877
	Hole 5A	7.9979	7.9979	7.9979	7.9979	7.9973
	Hole 6A	8.0108	8.0109	8.0109	8.0109	8.0098
	Central boss	10.0032	10.0032	10.0032	10.0031	10.0178
Cylindricity	Hole 1A	0.0051	0.0050	0.0055	0.0050	0.0050
	Hole 2A	0.0034	0.0034	0.0035	0.0034	0.0034
	Hole 3A	0.0021	0.0021	0.0022	0.0021	0.0021
	Hole 4A	0.0030	0.0030	0.0077	0.0030	0.0030
	Hole 5A	0.0006	0.0002	0.0010	0.0005	0.0006
	Hole 6A	0.0009	0.0010	0.0019	0.0010	0.0009
	Central boss	0.0151	0.0151	0.0159	0.0151	0.0151
Run-out (to D)	Cone	0.0142		0.0009	0.0086	
Flatness	Datum A	0.0008	0.0008	0.0008	0.0007	
	Back plane	0.0009	0.0009	0.0009	0.0009	
Perp (to A)	Datum B	0.0036	0.0036		0.0036	
Parallel (to B)	Back plane	0.0035	0.0035	0.0026	0.0035	

Table B-11 Software inter-comparison, scenario 1, CMM A, run 1, ref, CTC 1.

		Software package				
PMI Type	Feature	A	B	C	D	E
Size	Hole 1A	7.9868	7.9968	7.9868	7.9868	7.9537
	Hole 2A	7.9886	7.9886	7.9886	7.9886	7.9547
	Hole 3A	7.9912	7.9912	7.9912	7.9912	7.9556
	Hole 4A	7.9933	7.9933	7.9933	7.9933	7.9592
	Hole 5A	7.9976	7.9976	7.9976	7.9976	7.9905
	Hole 6A	8.0107	8.0107	8.0107	8.0107	8.0061
	Central boss	10.0011	10.0011	10.0011	10.0011	10.0600
Cylindricity	Hole 1A	0.0334	0.0334	0.0337	0.0334	0.0334
	Hole 2A	0.0358	0.0358	0.0366	0.0358	0.0357
	Hole 3A	0.0341	0.0341	0.0348	0.0341	0.0341
	Hole 4A	0.0353	0.0353	0.0355	0.0354	0.0353
	Hole 5A	0.0064	0.0064	0.0079	0.0064	0.0064
	Hole 6A	0.0051	0.0051	0.0052	0.0051	0.0051
	Central boss	0.0564	0.0564	0.0573	0.0564	0.0564
Run-out (to D)	Cone	0.0140		0.0083	0.0140	
Flatness	Datum A	0.0090	0.0090	0.0090	0.0090	
	Back plane	0.0023	0.0023	0.0023	0.0023	
Perp (to A)	Datum B	0.0036	0.0036		0.0036	
Parallel (to B)	Back plane	0.0050	0.0050	0.0047	0.0050	

Table B-12 Calibration data, CTC 1.

Calibration data, as measured on Zeiss F25 CMM (mm)				
PMI Type	Feature	Mean	Std Dev	Comment
Size	Hole 1A	7.98615	0.00001	Diameter of Gauss best-fit cylinder to 4 sections of 64 points measured at z = [-3.5|-2.5|-1.5|-0.5] mm
	Hole 2A	7.98788	0.00001	
	Hole 3A	7.99022	0.00010	
	Hole 4A	7.99228	0.00000	
	Hole 5A	7.99688	0.00000	
	Hole 6A	8.00951	0.00000	
	Central Boss	9.99924	0.00001	
Position (ABC) [7]	Hole 1A	0.00656	0.00017	GPS true position of hole, datum reference – primary datum top plane; secondary left hand (lower) block face; tertiary datum Hole 5A – shape of zone – diametral XY. Used least squares.
	Hole 2A	0.00553	0.00400	
	Hole 3A	0.00885	0.00067	
	Hole 4A	0.00894	0.00168	
	Hole 5A	N/A	N/A	
	Hole 6A	0.00736	0.00033	
	Central Boss	0.01575	0.00045	
Cylindricity	Hole 1A	0.03280	0.00001	Min zone cylindricity of Gauss best-fit cylinder to 4 sections of 64 pt measured at z = [-3.5|-2.5|-1.5|-0.5] mm
	Hole 2A	0.03250	0.00001	
	Hole 3A	0.03364	0.00315	
	Hole 4A	0.03583	0.00001	
	Hole 5A	0.00719	0.00002	
	Hole 6A	0.00211	0.00006	
	Central Boss	0.05197	0.00001	
Run-out (D)	Cone	N/A	N/A	Tolerance not evaluated
Flatness	Datum A	0.00136	0.00001	Min zone flatness of meas points on block top plane
	Non-datum plane	0.00104	0.00001	Flatness of Gauss best- fit plane to 4 lines of 18 pt measured at z = [-3.5|-2.5|-1.5|-0.5] mm on right hand (upper) block face
Perp (A)	Datum B	N/A	N/A	Tolerance not evaluated
Prof (ABC)	Non-datum plane	N/A	N/A	Tolerance not evaluated
Parallel (B)	Non-datum plane	0.00191	0.00001	Min zone parallelism of Gauss best-fit planes to lines, points measured at 4 heights on left hand and right hand (upper) block faces

[7] Range is shown instead of standard deviation for position because there were only two results

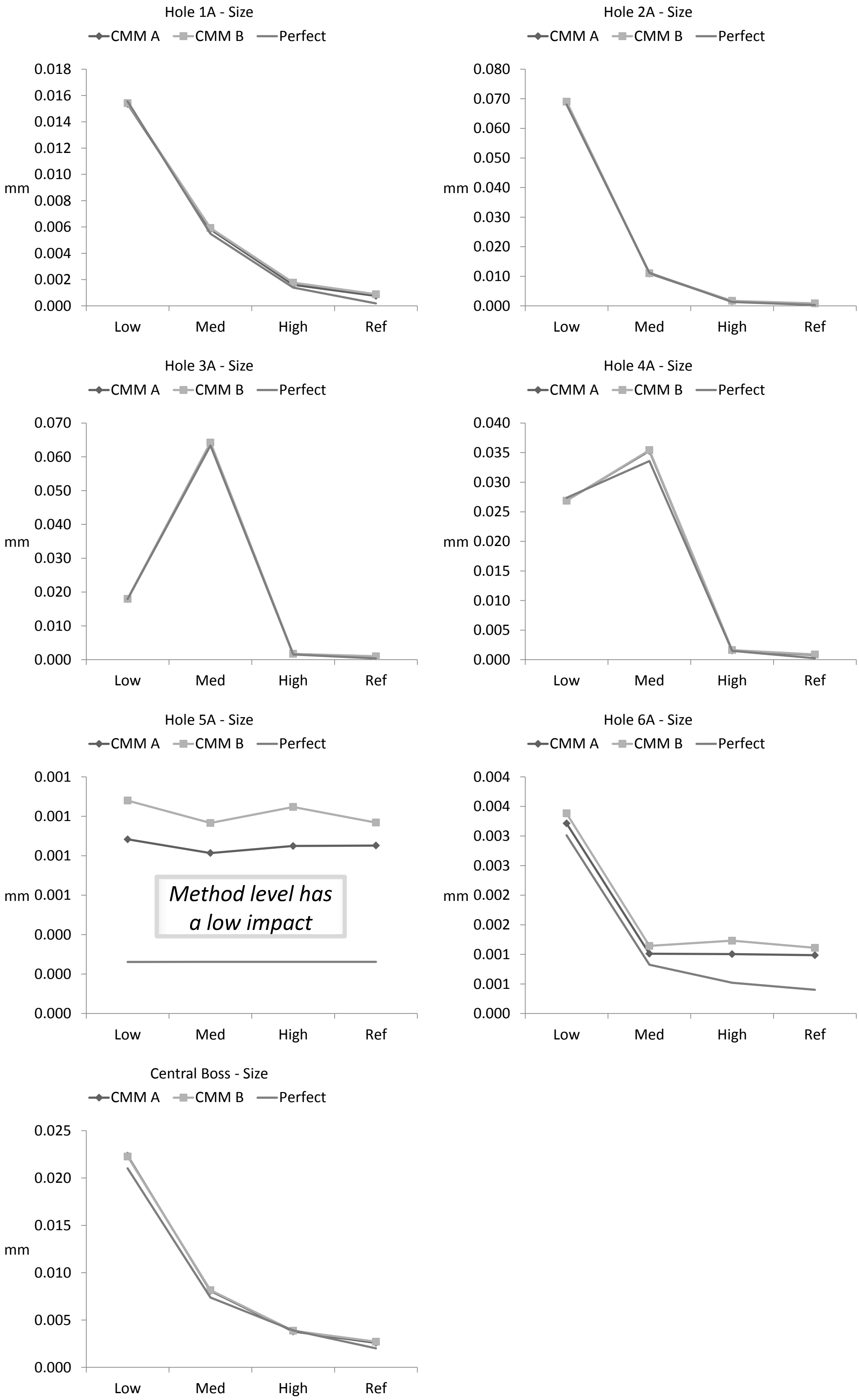

Figure B-1 U_{sim}, size of holes and central boss, CTC 1.

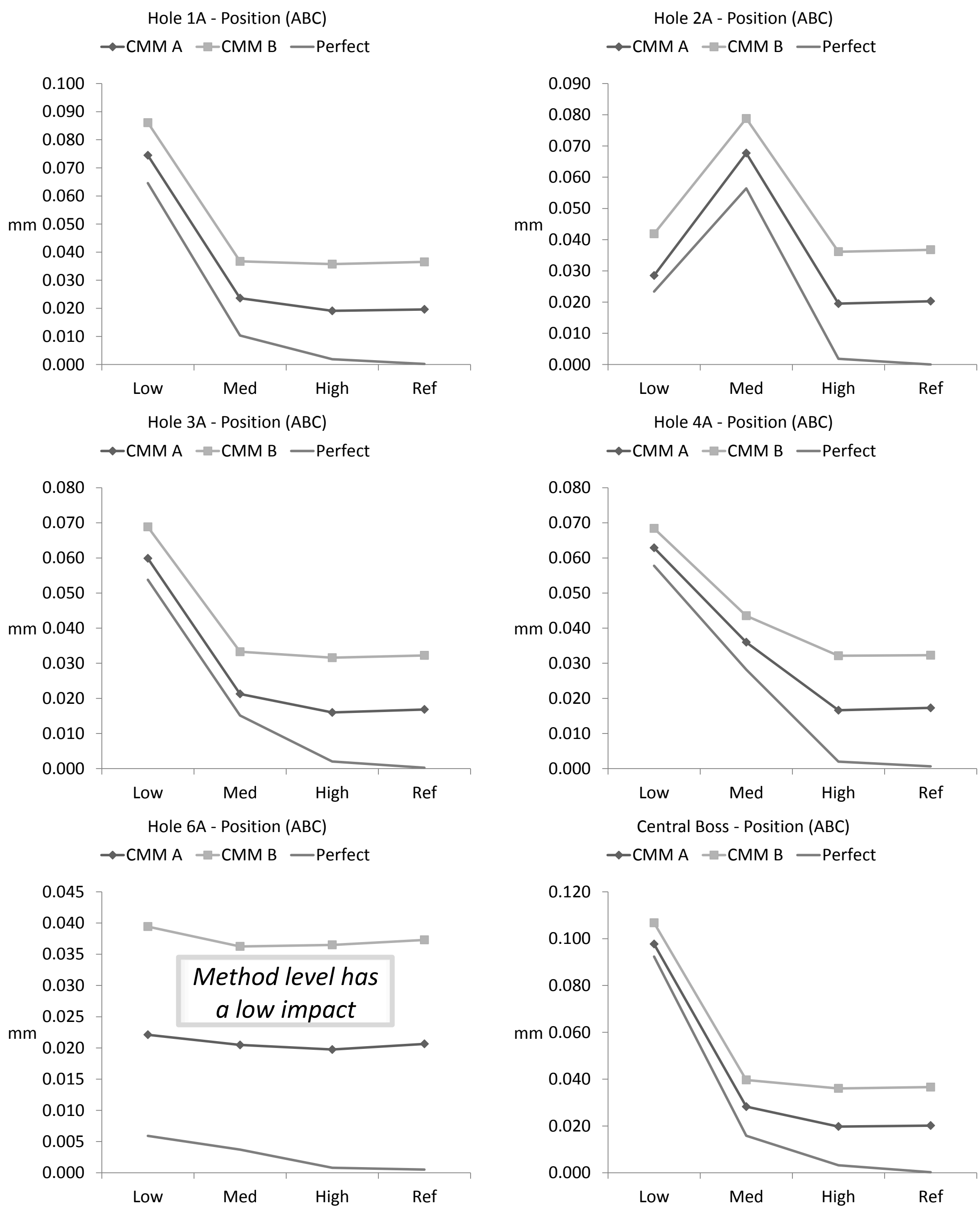

Figure B-2 U_{sim}, position of holes and central boss, CTC 1.

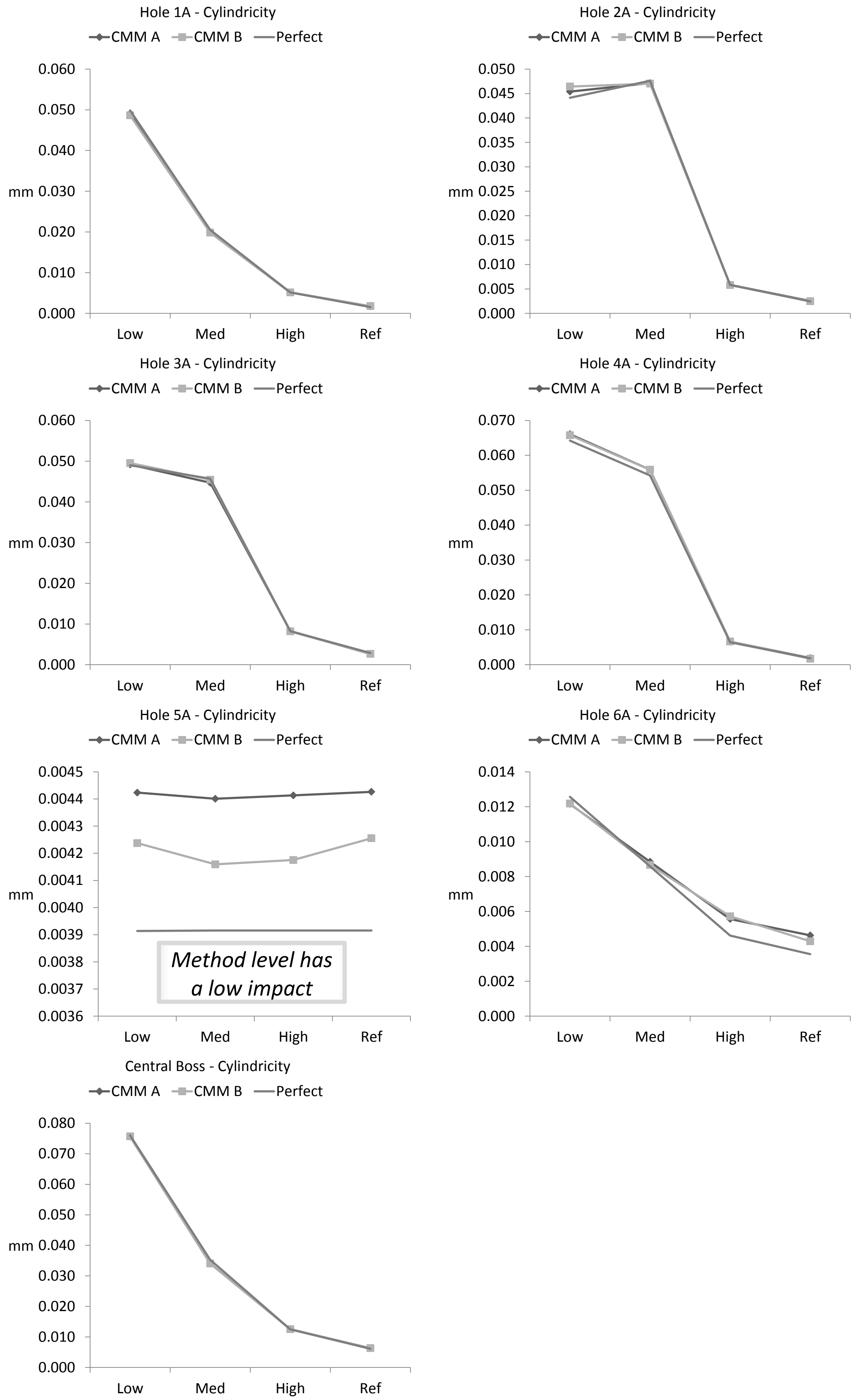

Figure B-3 U_{sim}, cylindricity of holes and central boss, CTC 1.

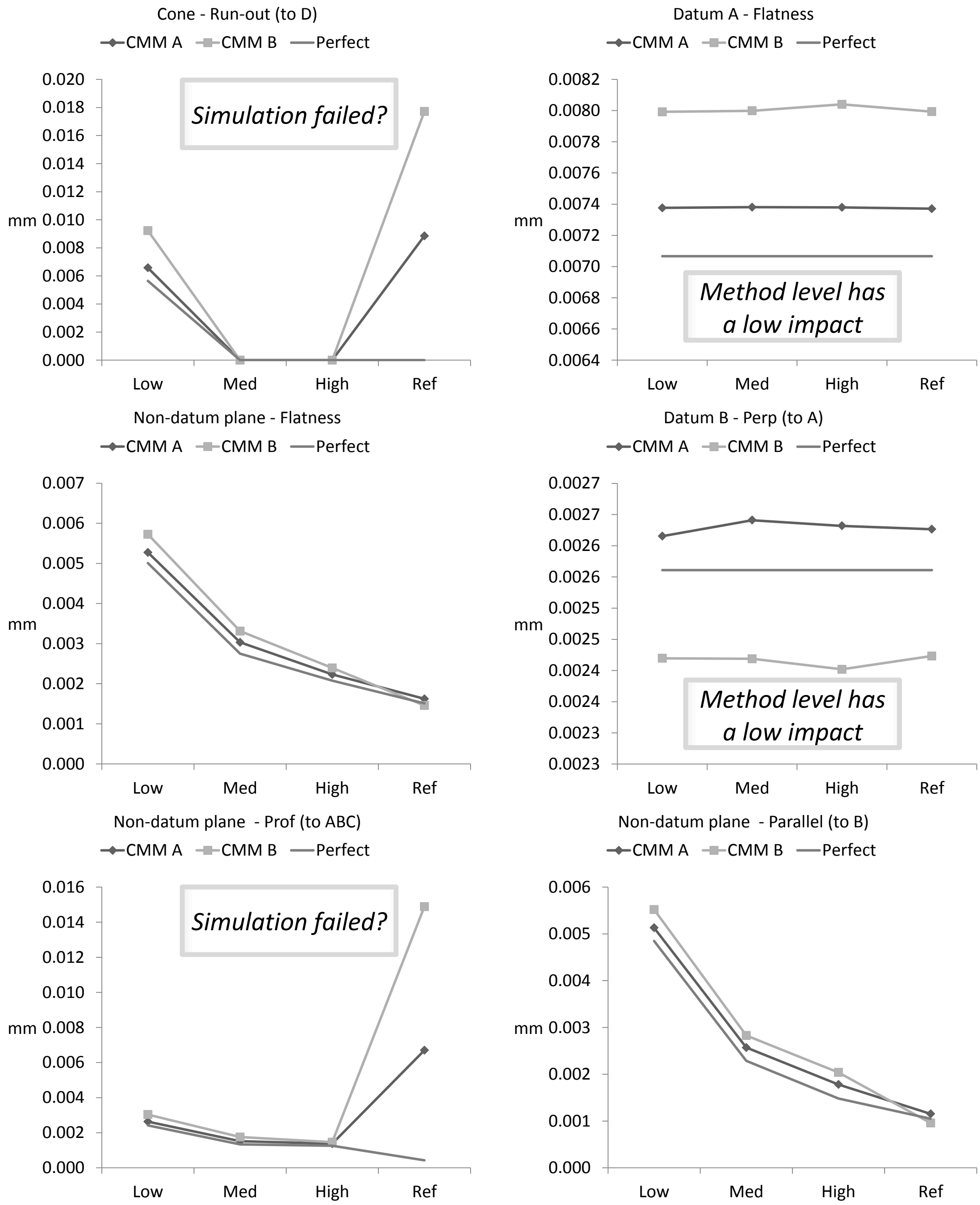

Figure B-4 U_{sim}, other PMI, CTC 1.

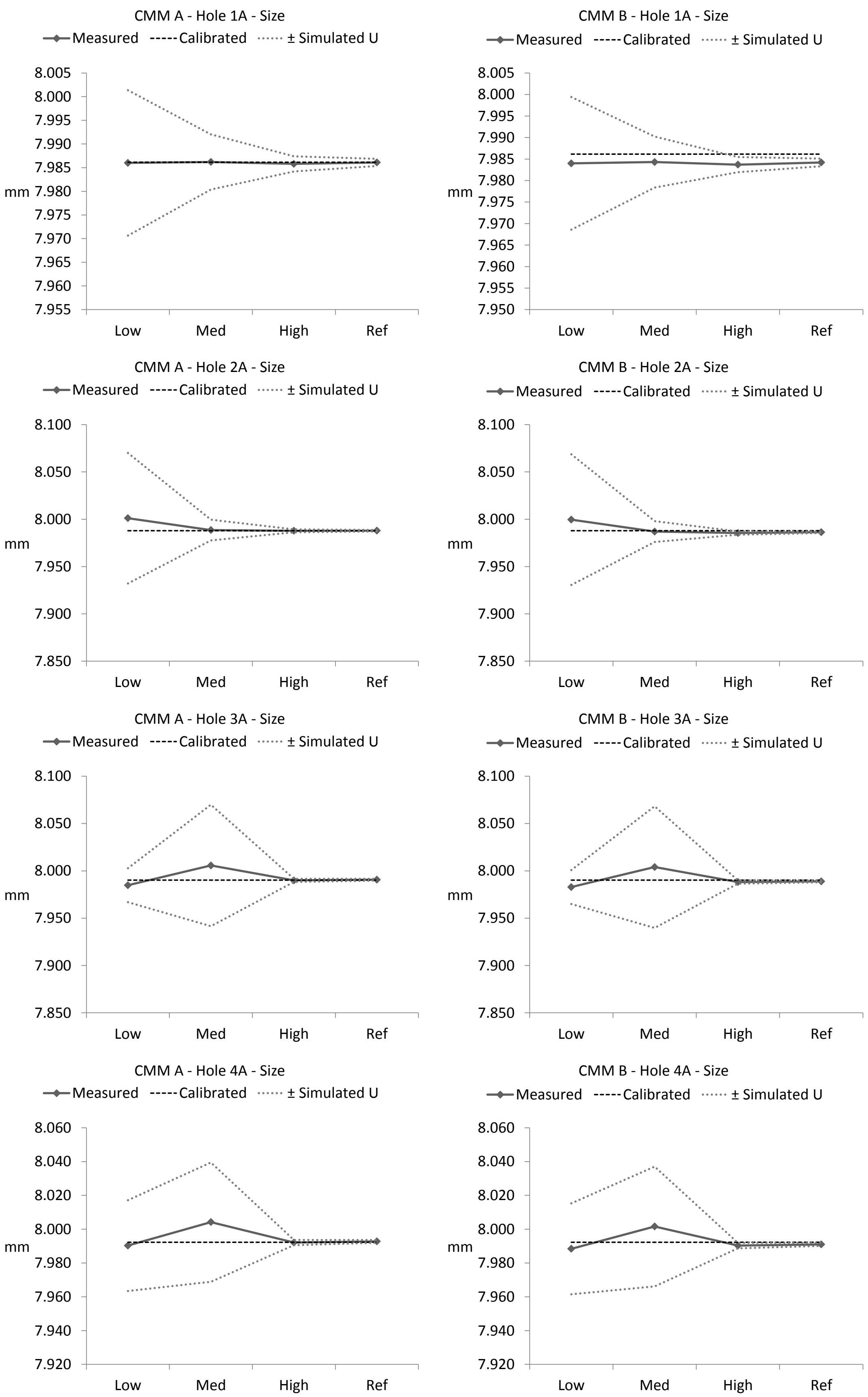

Figure B-5 Measured value and U_{sim}, size, two CMMs, CTC 1 (fig. 1 of 2).

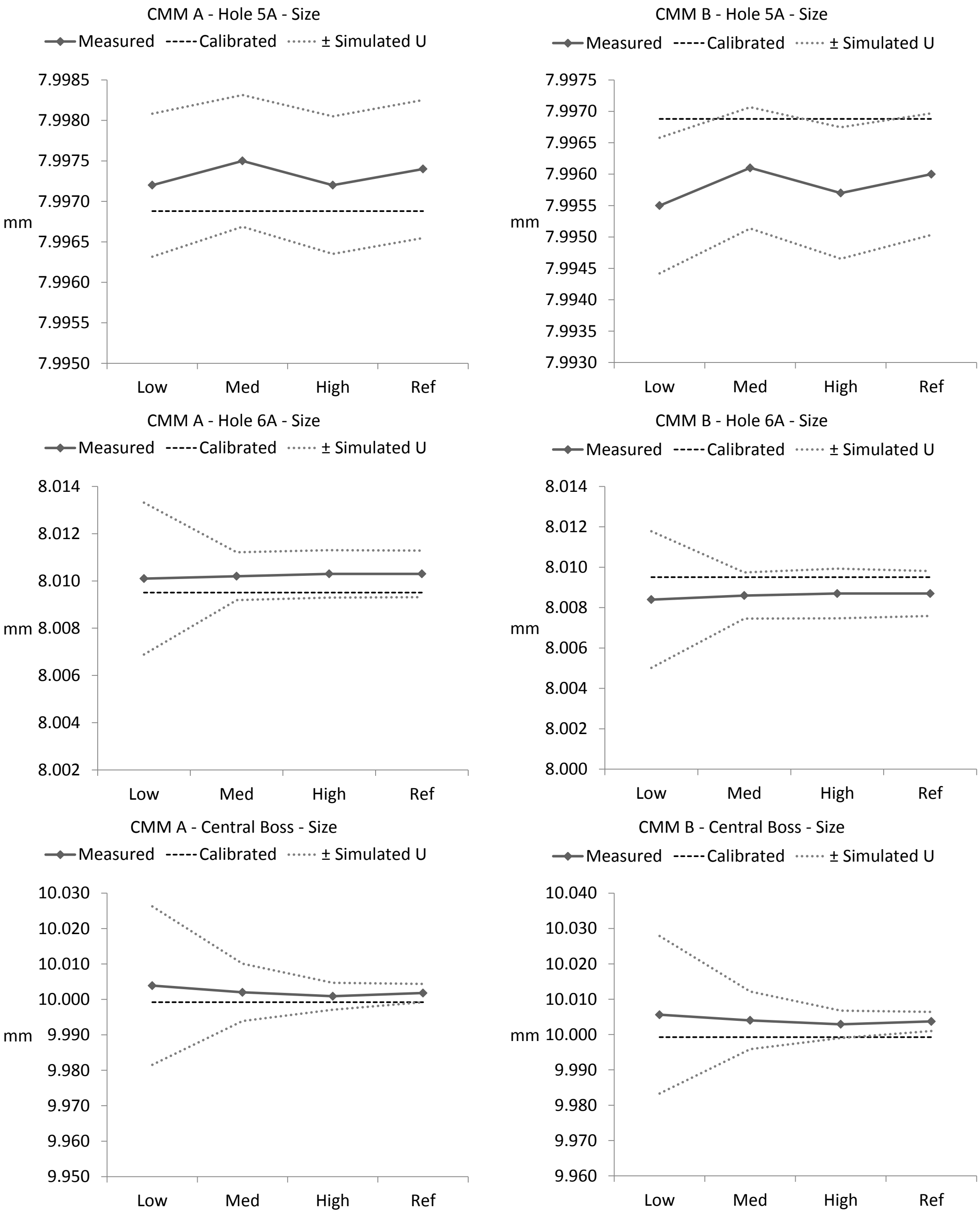

Figure B-6 Measured value and U_{sim}, size, two CMMs, CTC 1 (fig. 2 of 2).

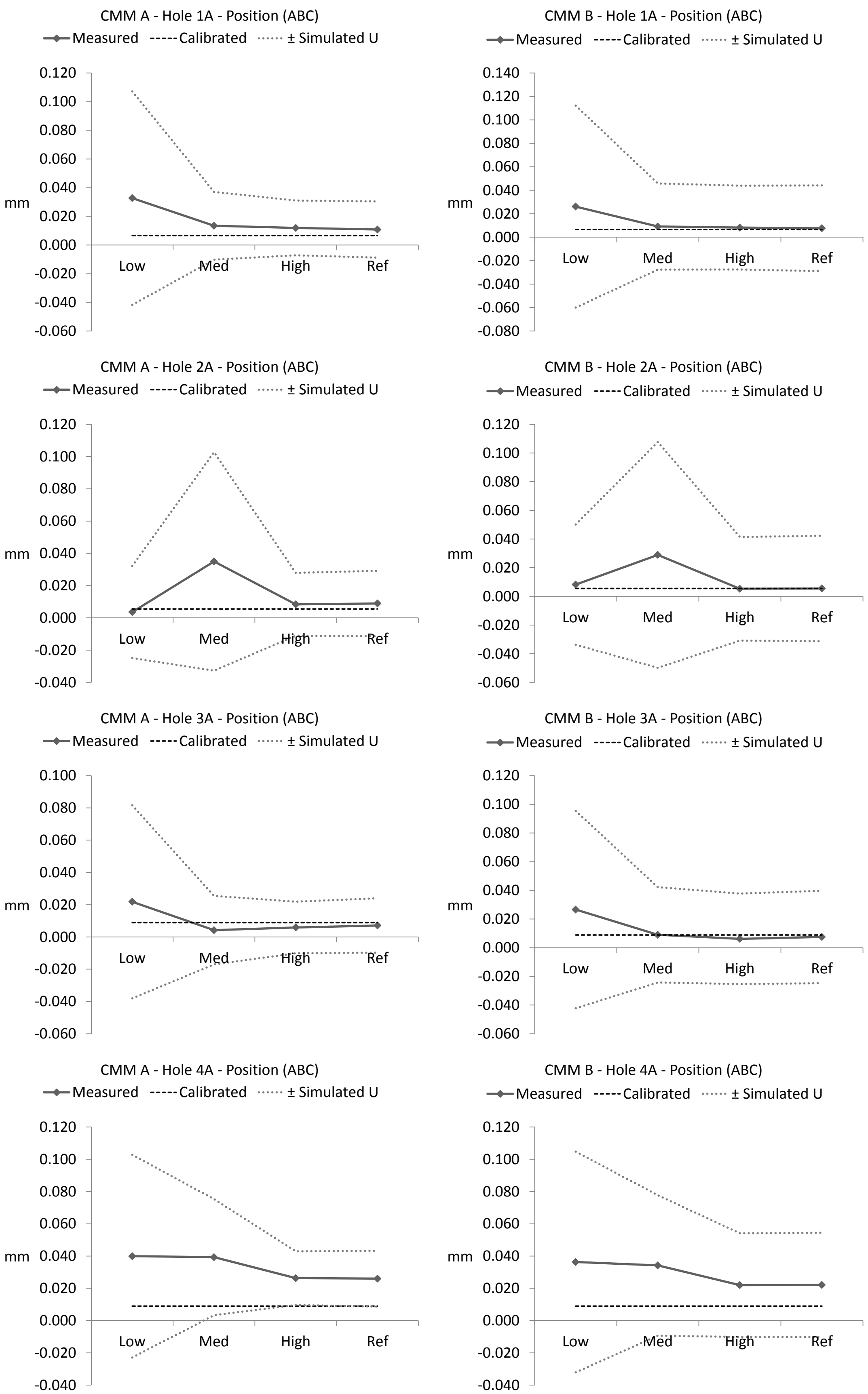

Figure B-7 Measured value and U_{sim}, position, two CMMs, CTC 1 (fig. 1 of 2).

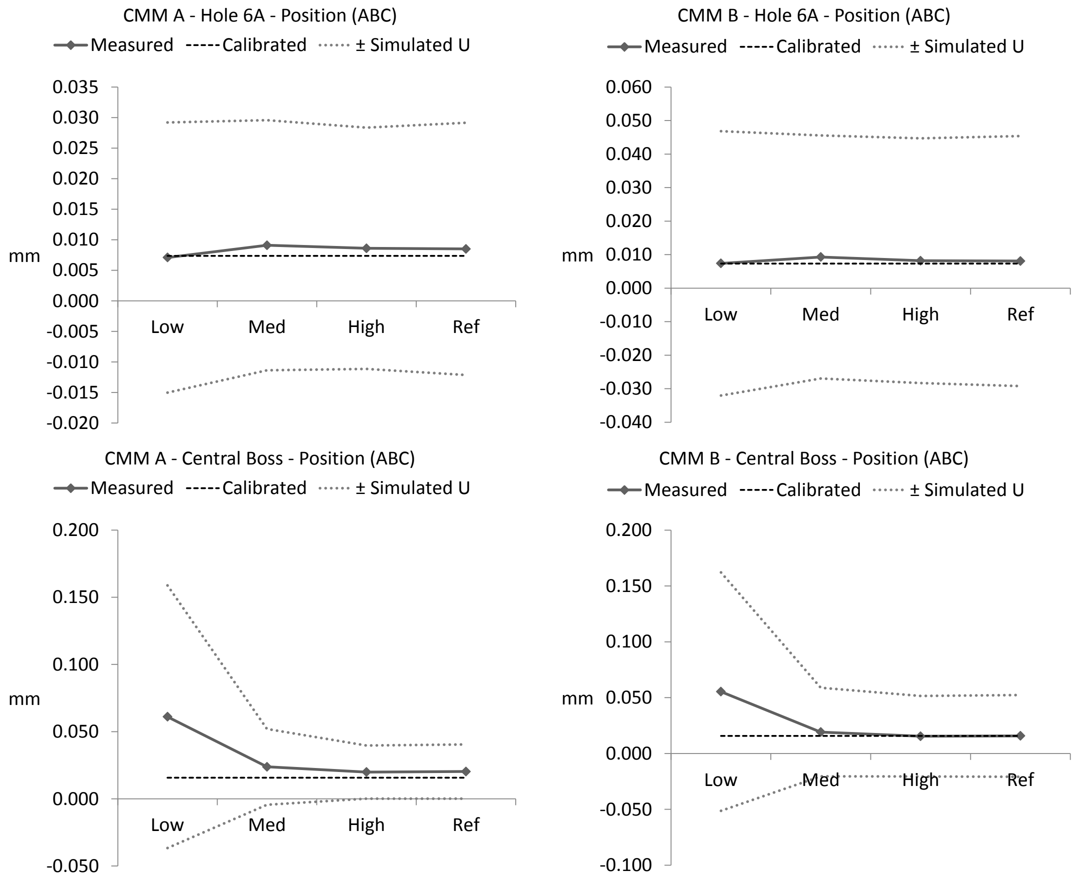

Figure B-8 Measured value and U_{sim}, position, two CMMs, CTC 1 (fig. 2 of 2).

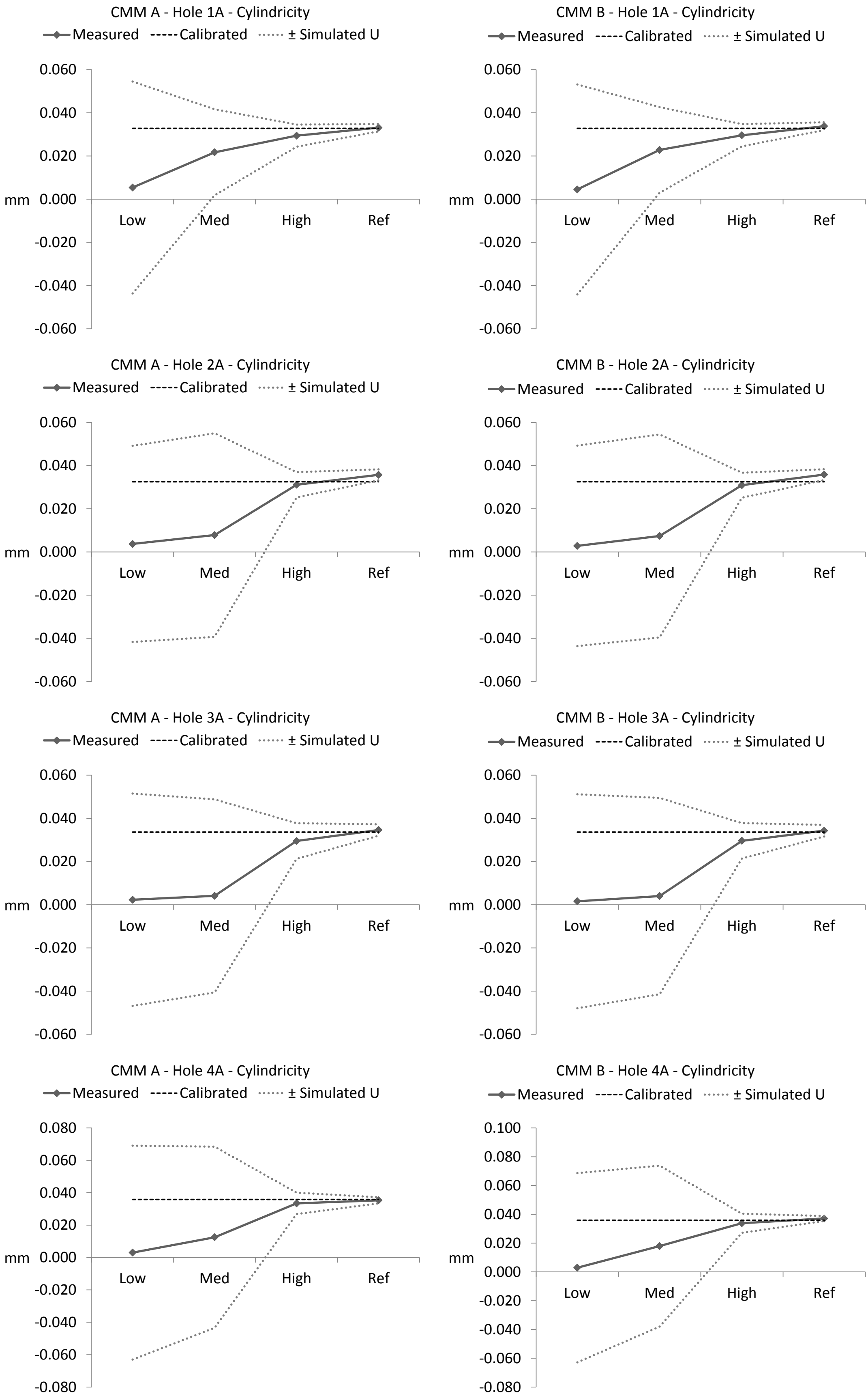

Figure B-9 Measured value and U_{sim}, cylindricity, two CMMs, CTC 1 (fig. 1 of 2).

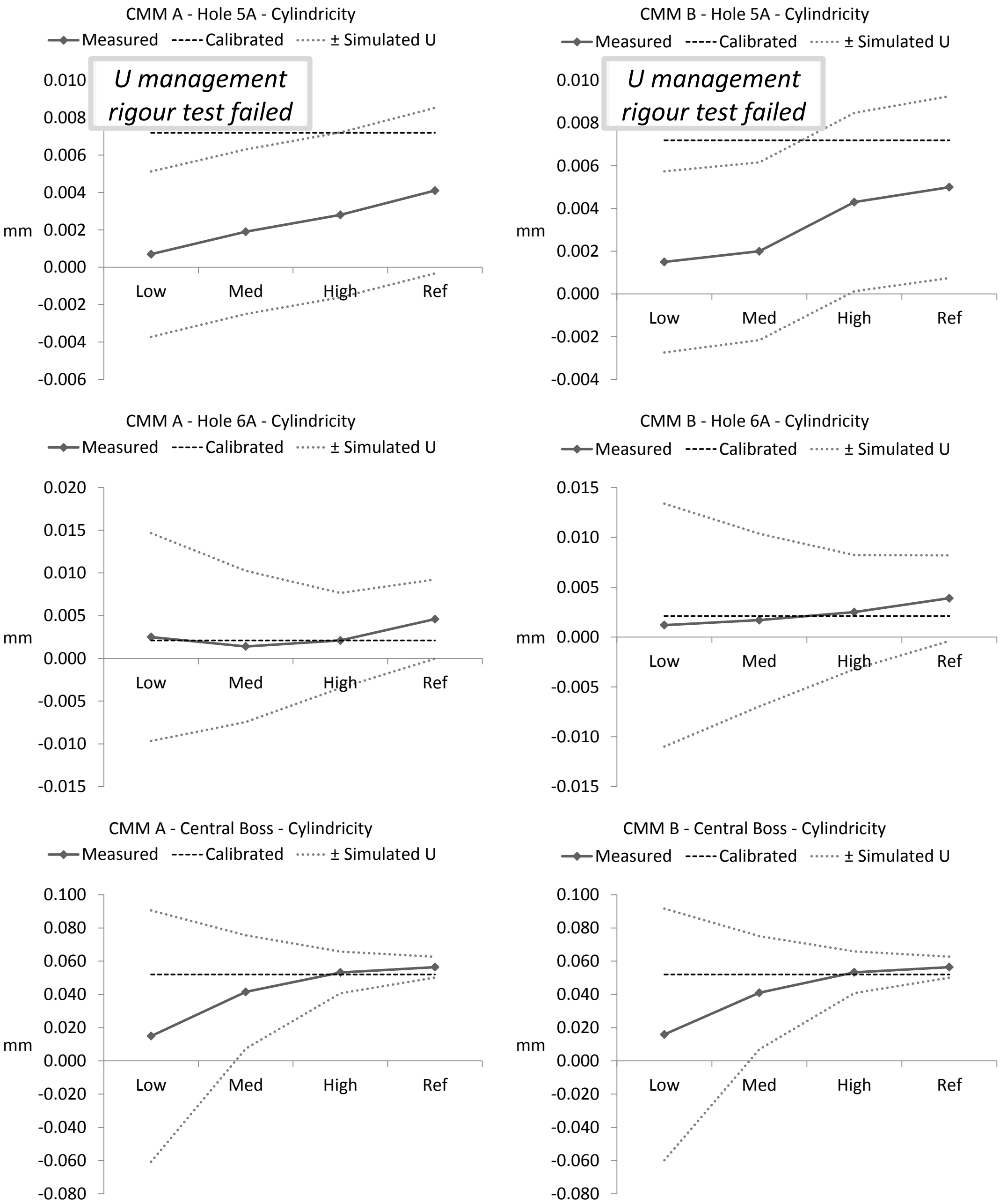

Figure B-10 Measured value and U_{sim}, cylindricity, two CMMs, CTC 1 (fig. 2 of 2).

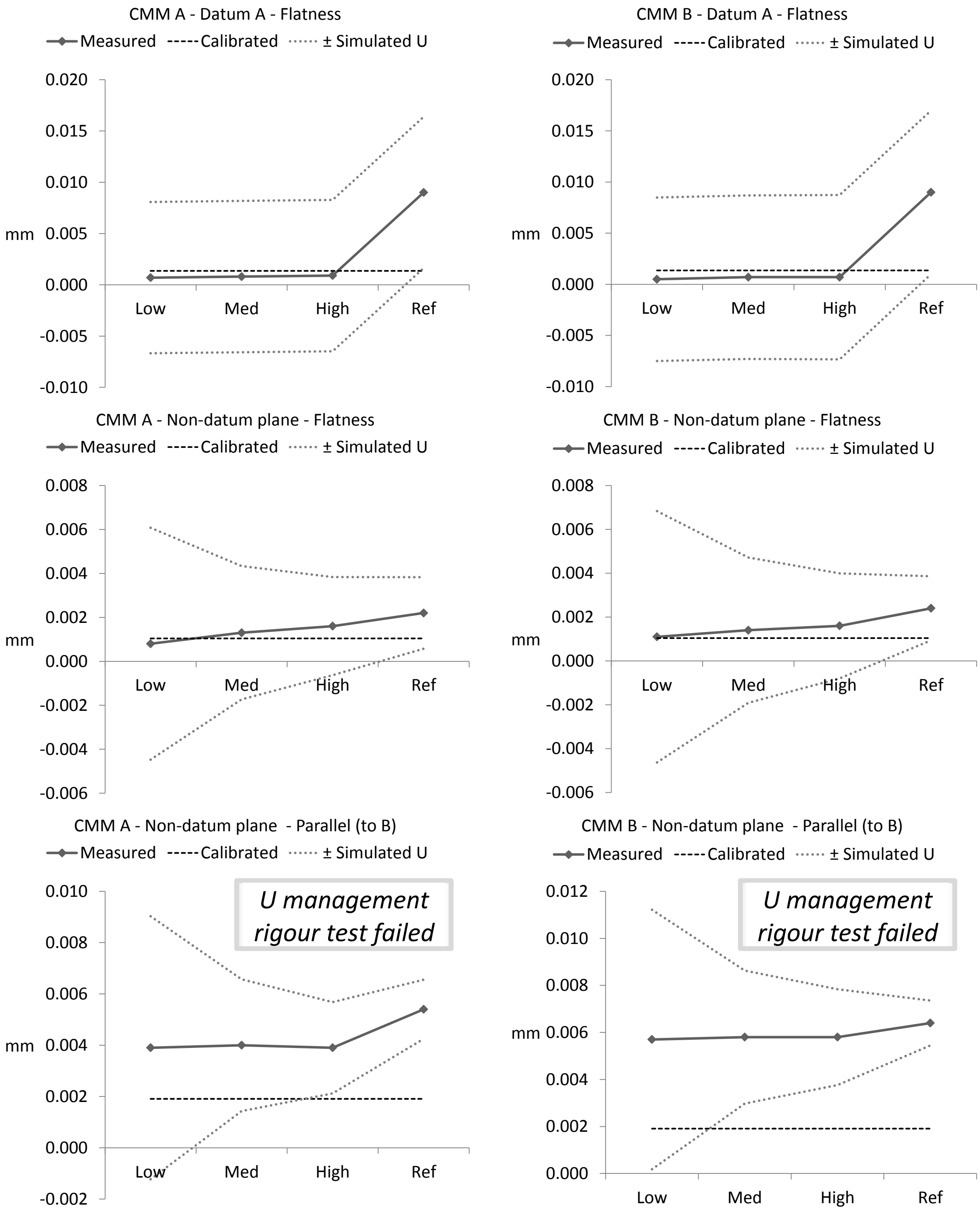

Figure B-11 Measured value and U_{sim}, other PMI, two CMMs, CTC 1.

B.3 CTC 2: AEC test block

Table B-13 PMI and features, CTC 2.

PMI Name	PMI Type	Feature
TOL06_DB	Linear	FACE_RIGHT
TOL08_PAR	Parallelism	FACE_RIGHT
TOL10_PR	Surface profile	CURVE_SLOT_FACE_01
TOL10_PR	Surface profile	CURVE_SLOT_FACE_02
TOL11_PAR	Parallelism	FACE_FRONT
TOL12_AN	Angularity	CORNER_FACE
TOL13_PR	Surface profile	CORNER_FACE
TOL14_1_TP	Position	HOLE_5MM_01
TOL14_2_TP	Position	HOLE_5MM_02
TOL15_1_D	Diameter	HOLE_5MM_01
TOL15_2_D	Diameter	HOLE_5MM_02
TOL16_DB	Linear	FACE_FRONT
TOL18_TP	Position	DATUM_Z : Z
TOL19_D	Diameter	DATUM_Z : Z
TOL36_PAR	Parallelism	HOLE_50MM_DEPTH
TOL38_TP	Position	HOLE_50MM
TOL39_D	Diameter	HOLE_50MM
TOL41_CYL	Cylindricity	HOLE_50MM
TOL42_D	Diameter	DATUM_Y : Y
TOL43_PE	Perpendicularity	DATUM_Y : Y

Notes:

1. PMI related to the angled hole was evaluated through measurement, though not analysed in the UES because there were difficulties aligning the nominal points between the PLM and UES systems.
2. The surface profile on the curved slot was analysed for the two large arcs only, and not evaluated as a group.

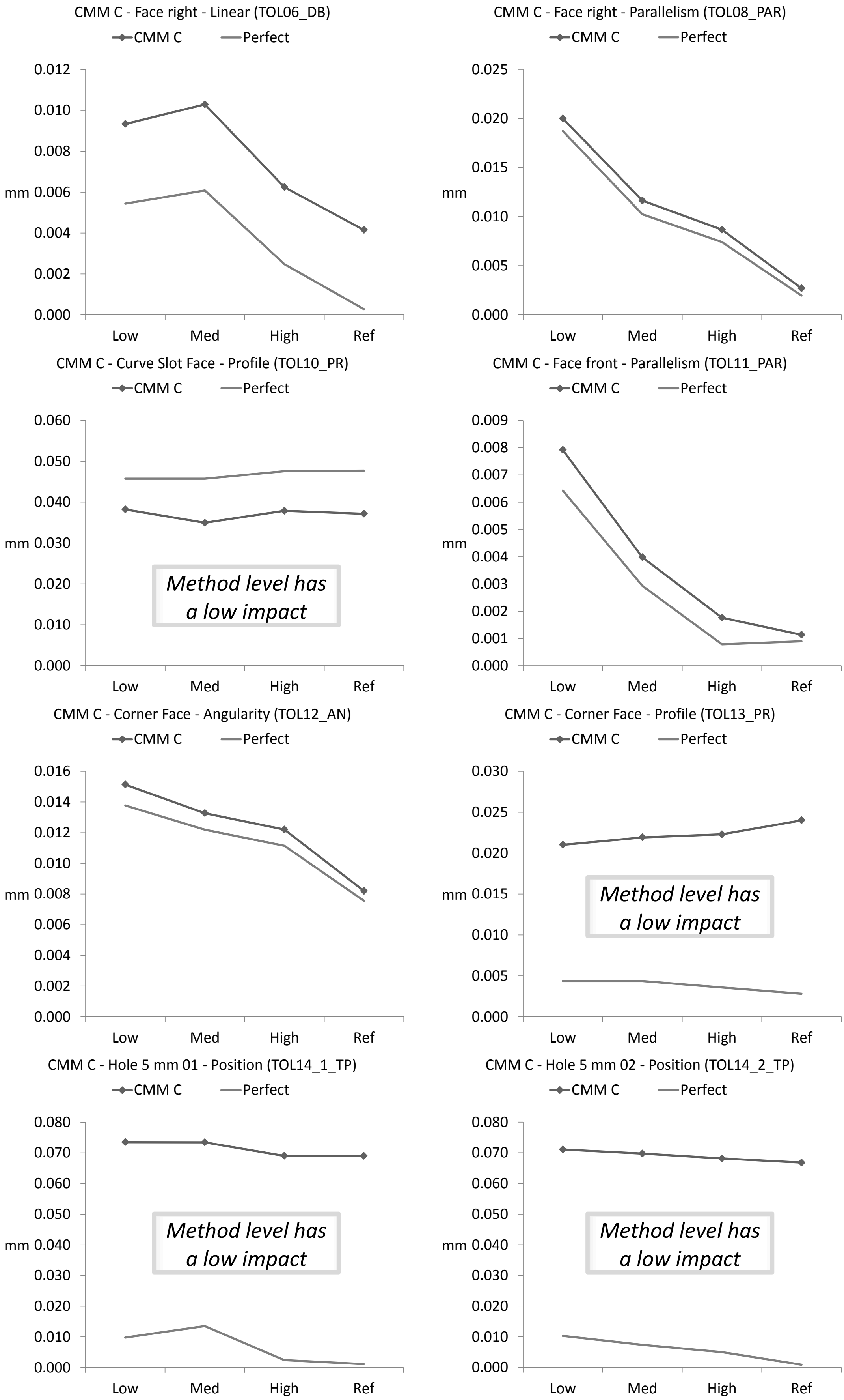

Figure B-12 U_{sim}, block 1, CTC 2 (fig. 1 of 3).

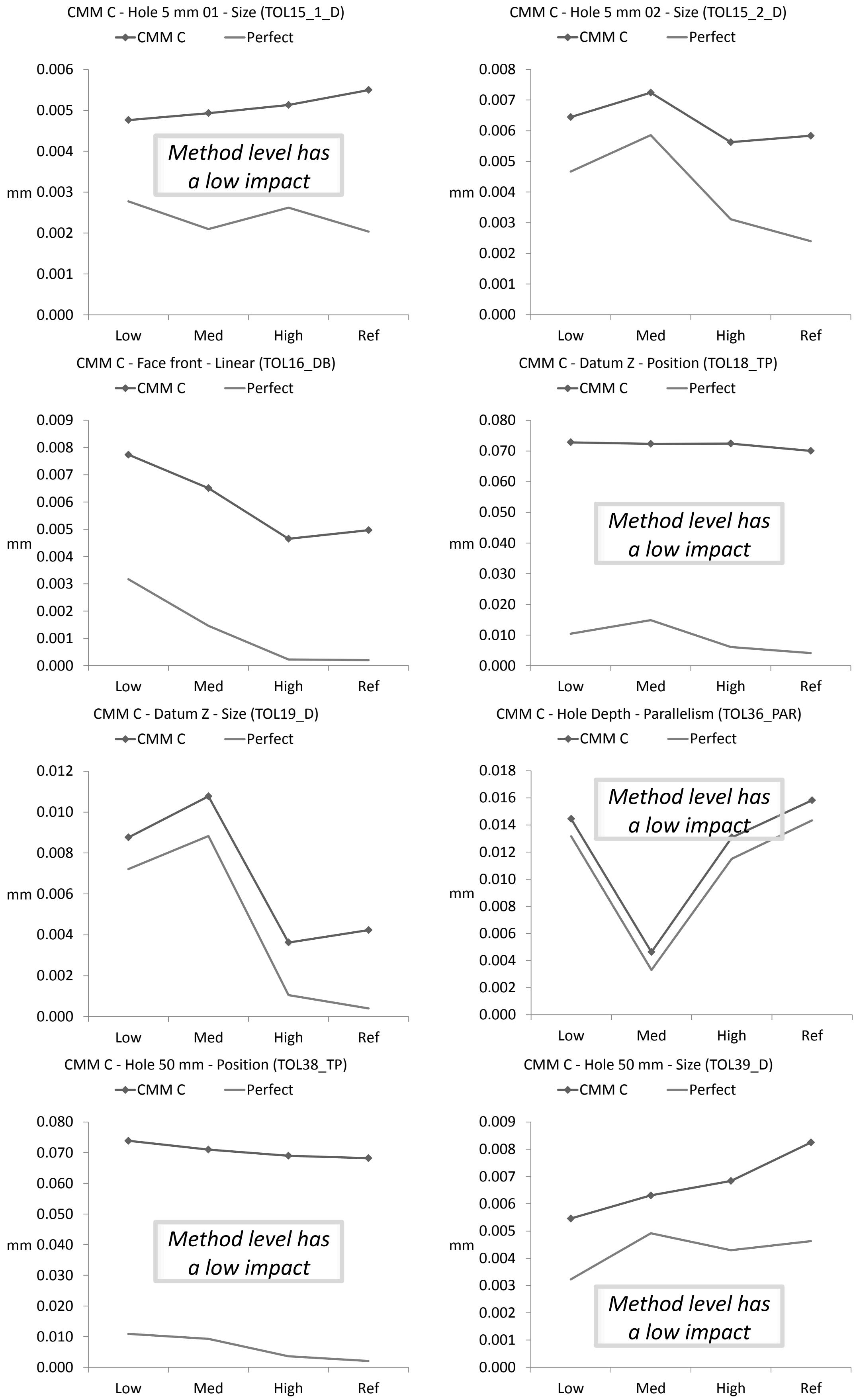

Figure B-13 U_{sim}, block 1, CTC 2 (fig. 2 of 3).

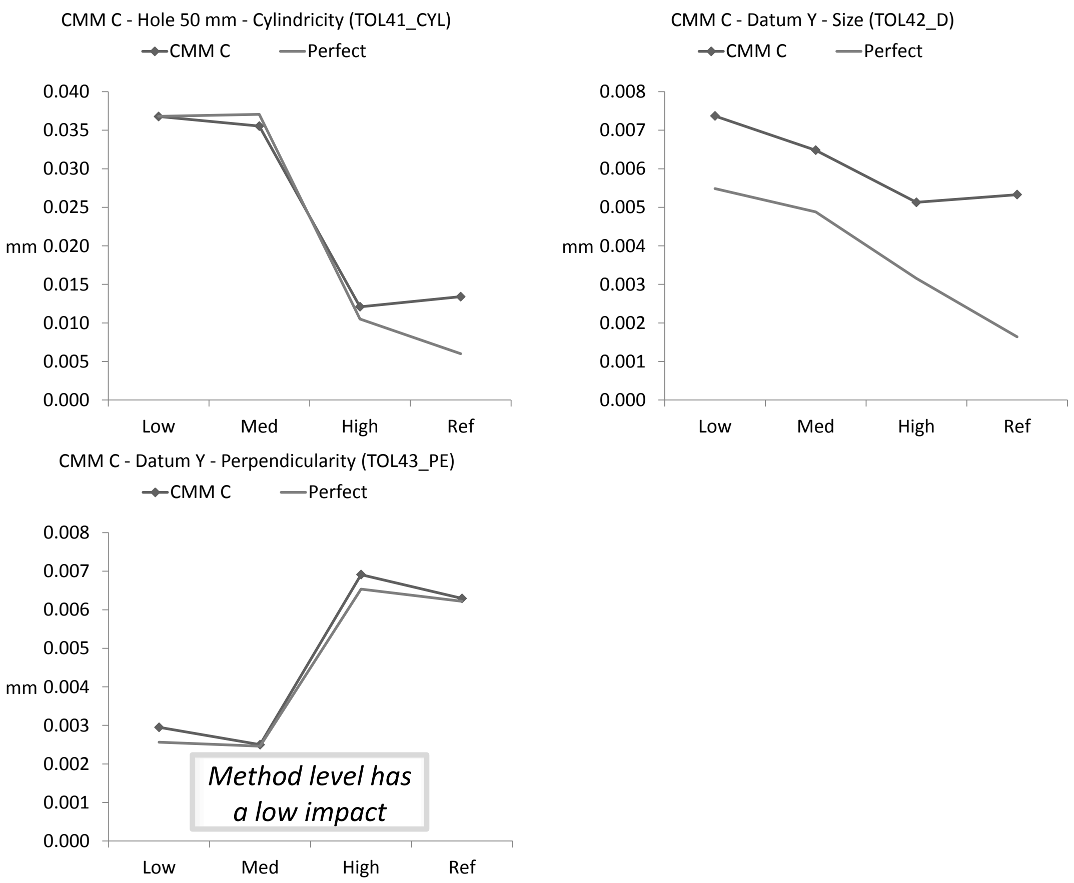

Figure B-14 U_{sim}, block 1, CTC 2 (fig. 3 of 3).

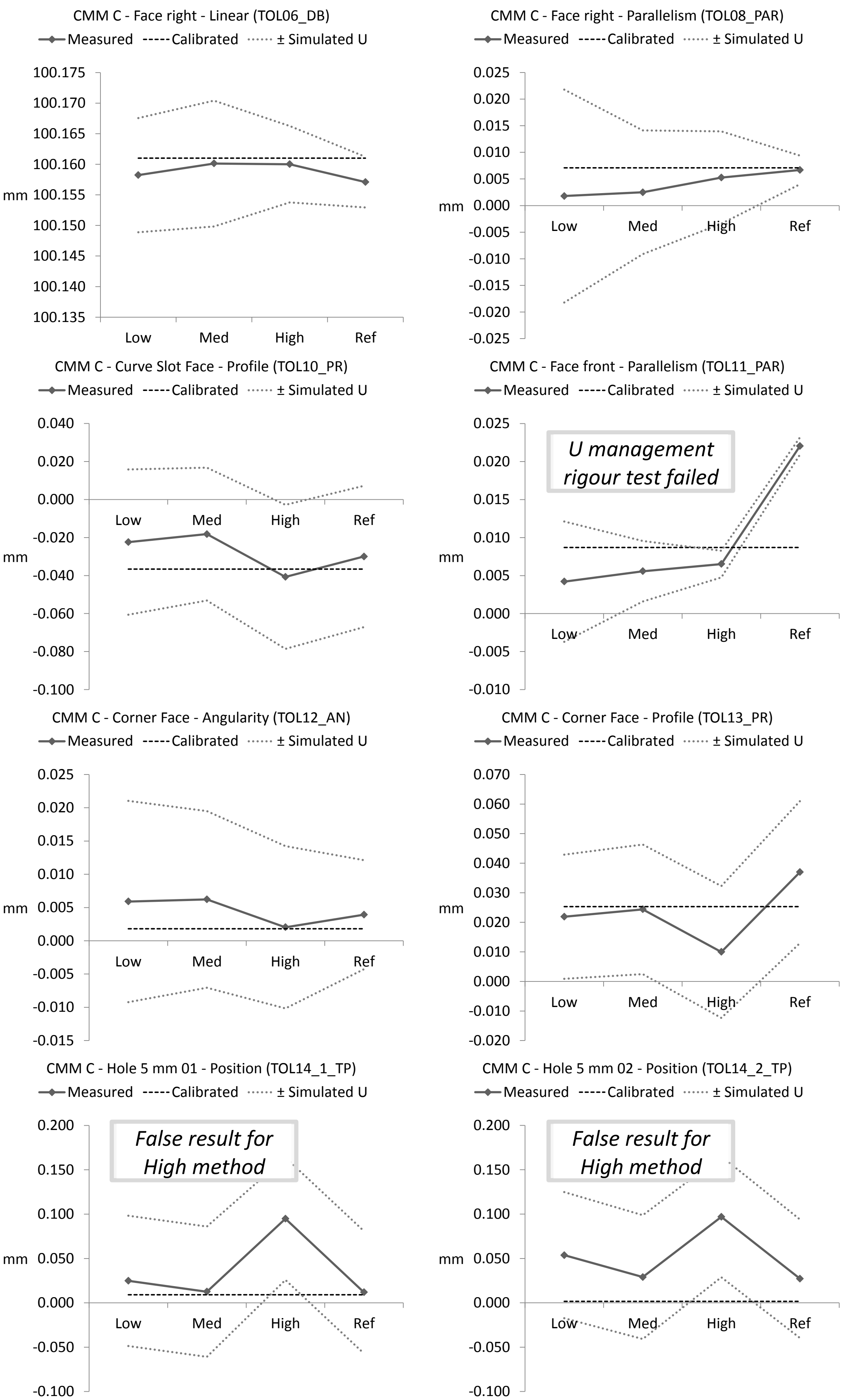

Figure B-15 Measured value and U_{sim}, block 1, CTC 2 (fig. 1 of 3).

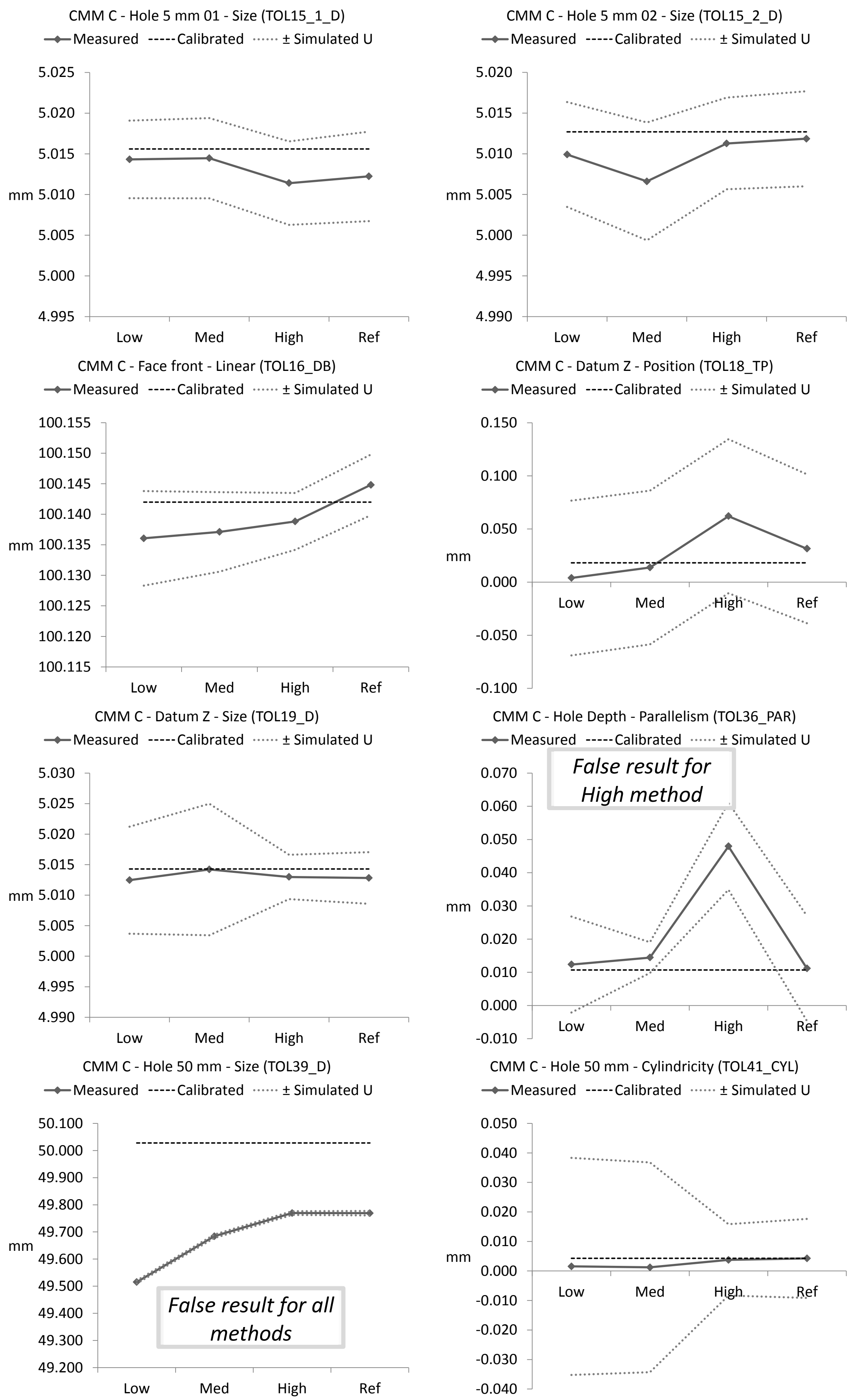

Figure B-16 Measured value and U_{sim}, block 1, CTC 2 (fig. 2 of 3).

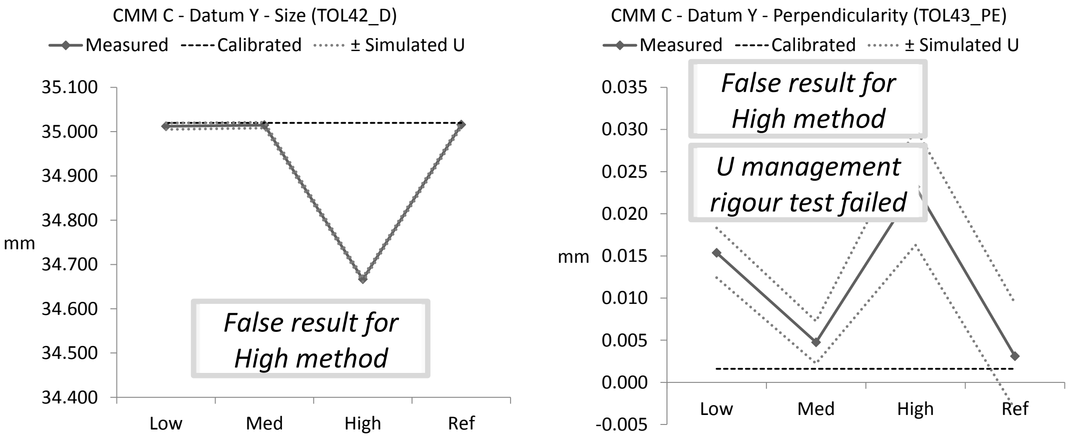

Figure B-17 Measured value and U_{sim}, block 1, CTC 2 (fig. 3 of 3).

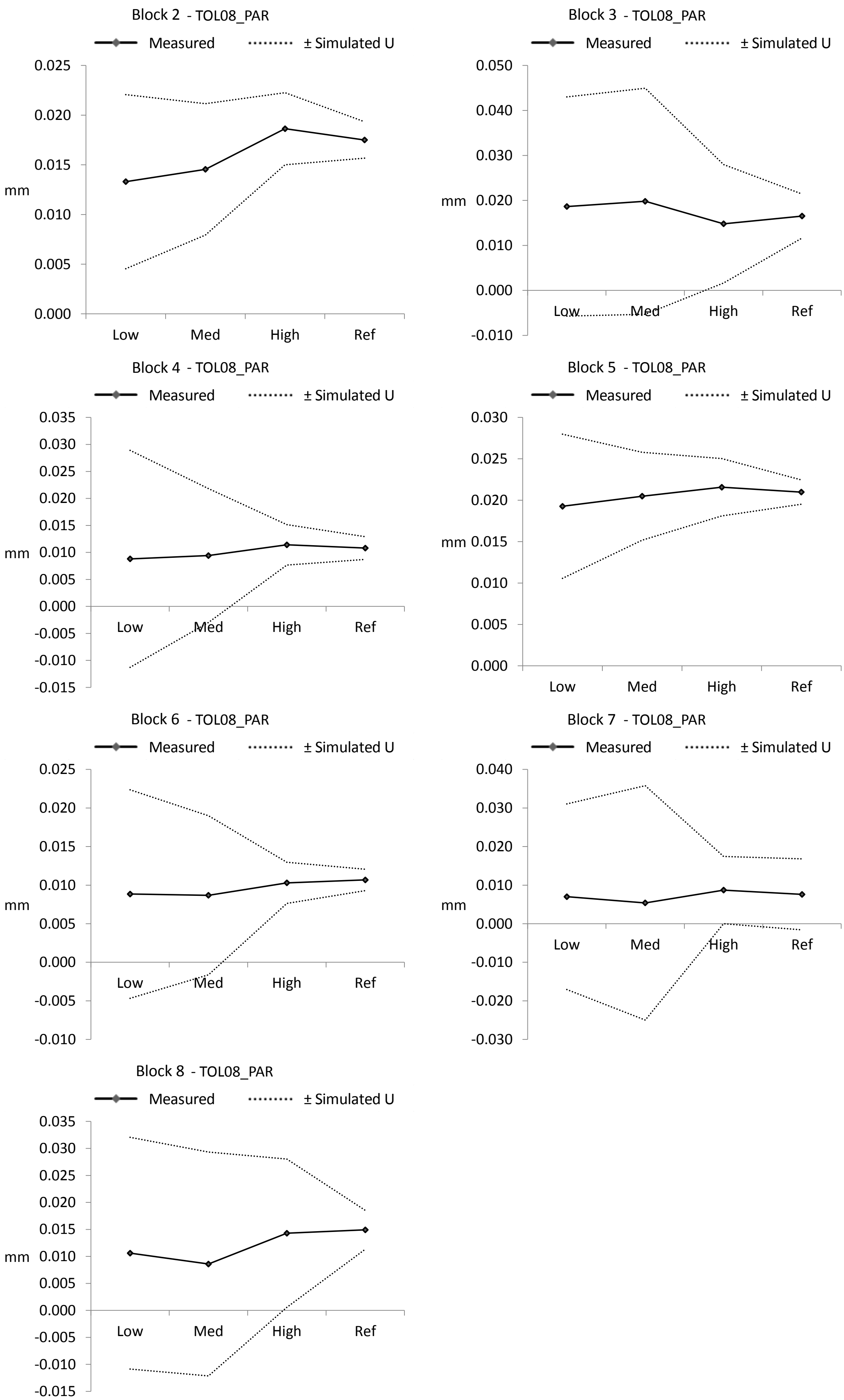

Figure B-18 Measured value and U_{sim}, parallelism, all blocks, CTC 2.

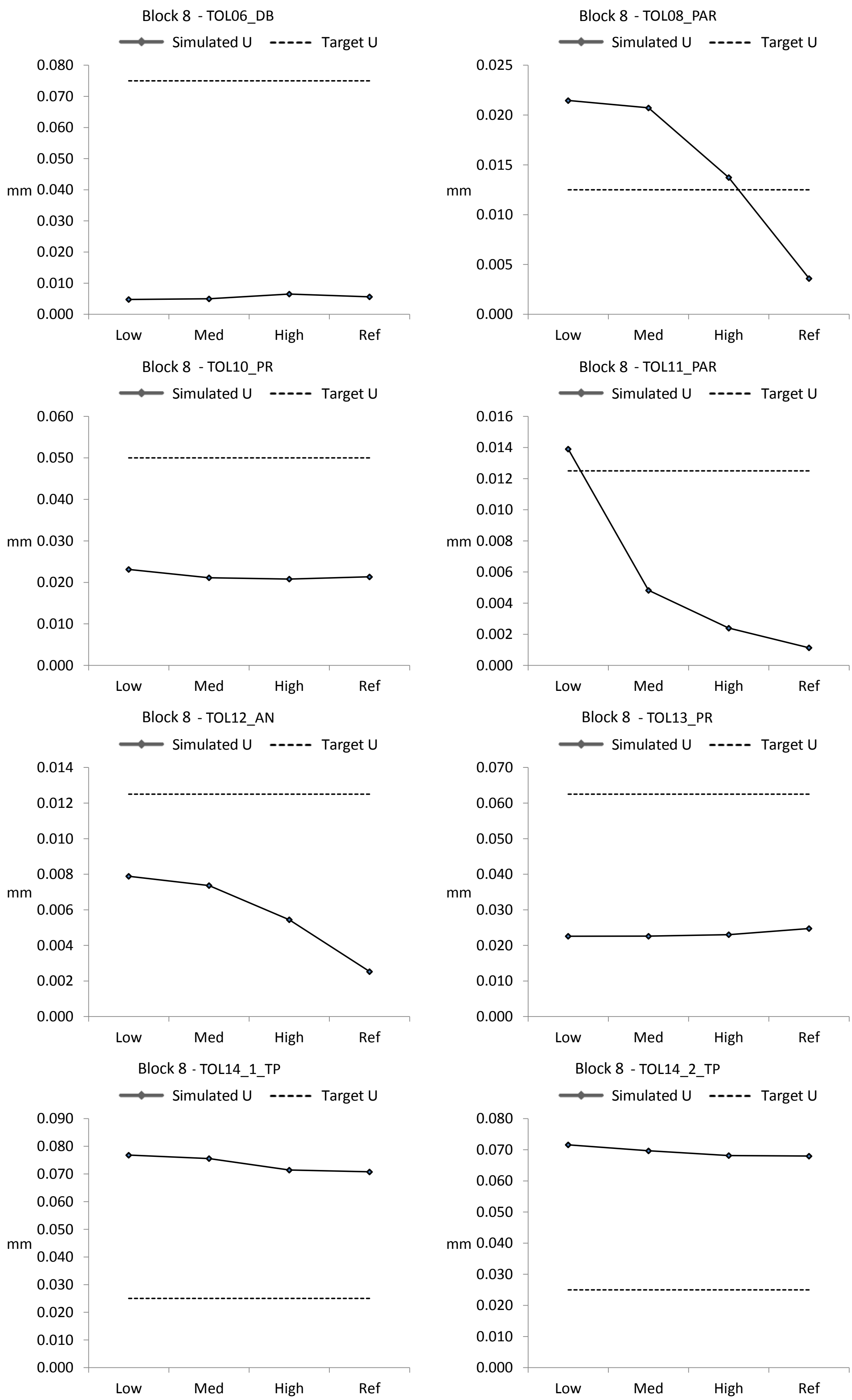

Figure B-19 U_{sim} and U_T, block 8, CTC 2 (fig. 1 of 3).

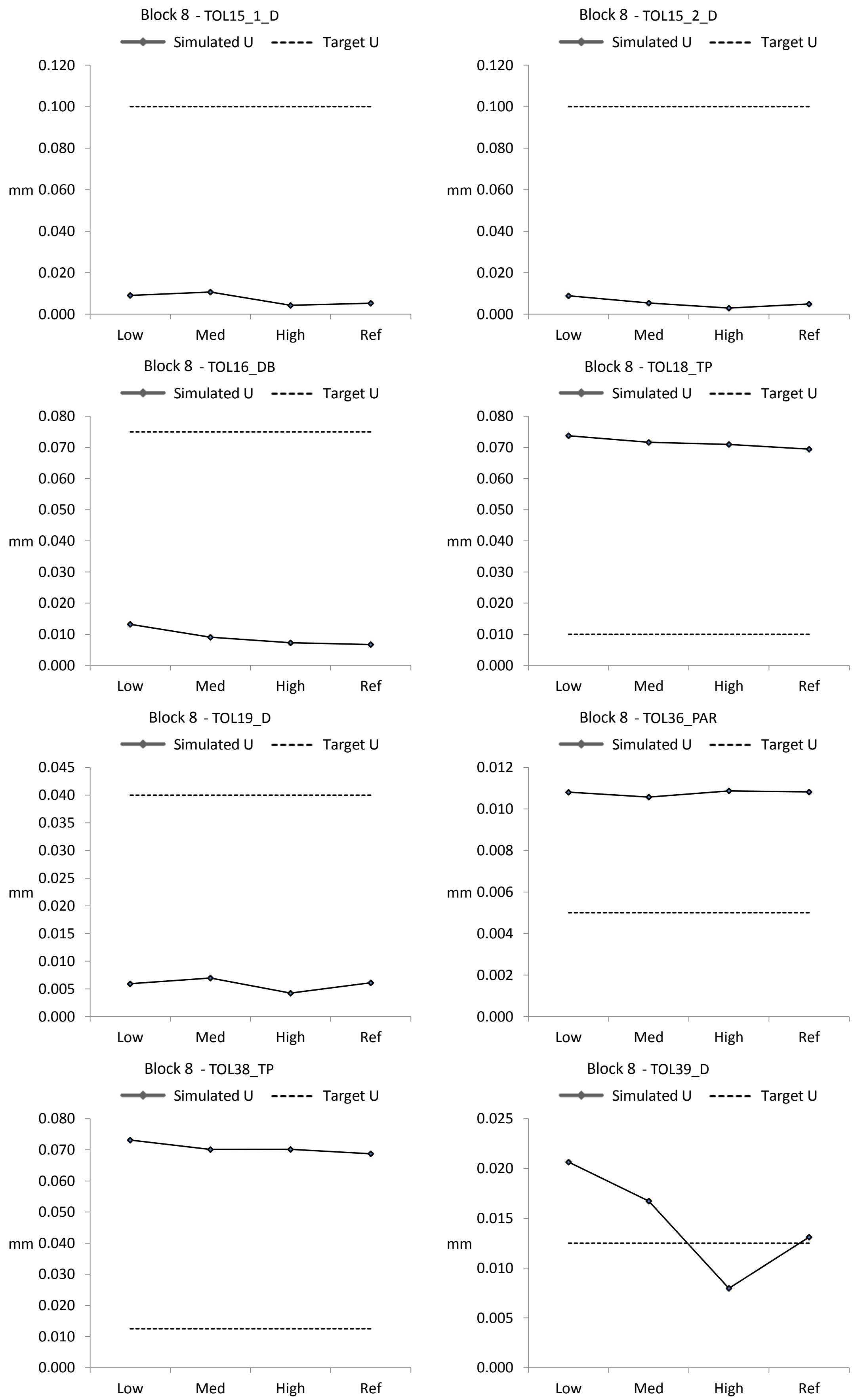

Figure B-20 U_{sim} and U_T, block 8, CTC 2 (fig. 2 of 3).

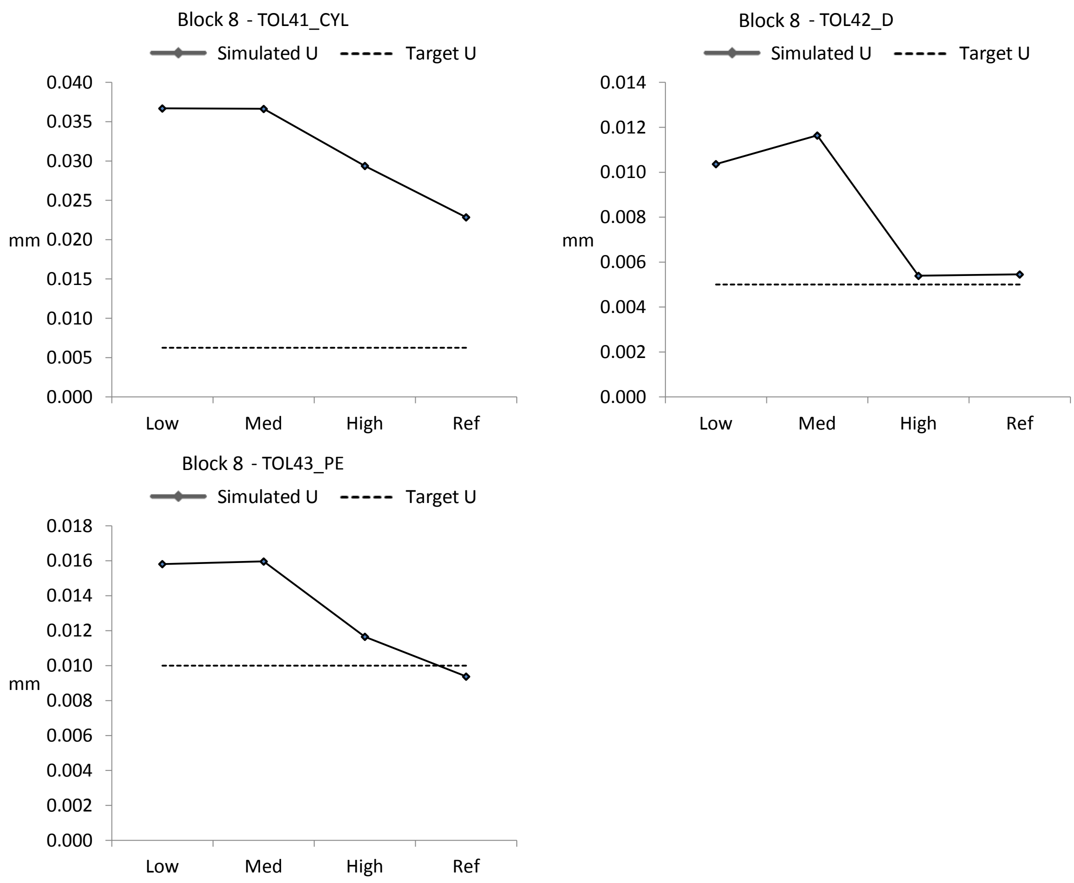

Figure B-21 U_{sim} and U_{T}, block 8, CTC 2 (fig. 3 of 3).

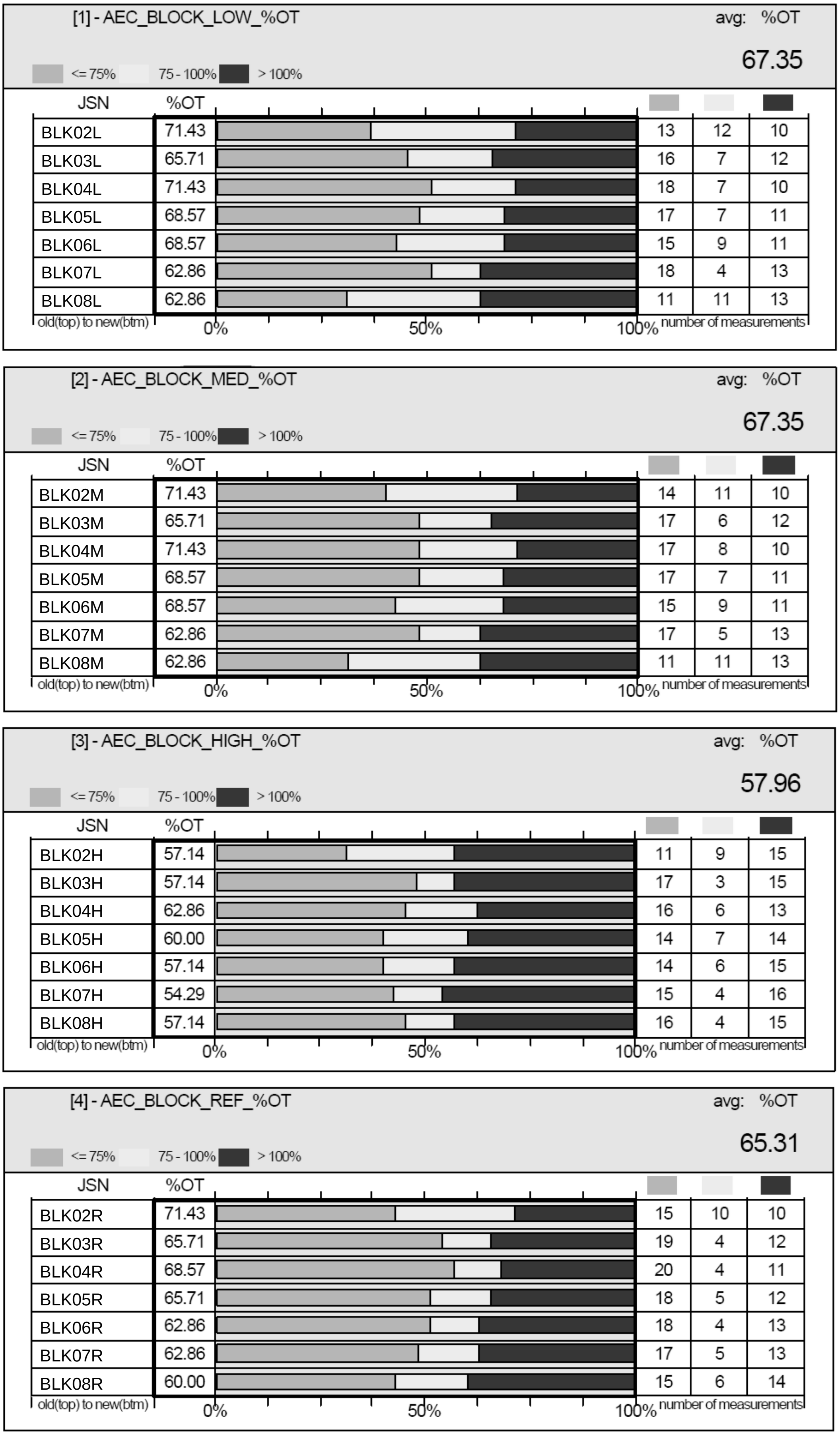

Figure B-22 Percentage on target (%OT) by method level, CTC 2.

B.4 CTC 3: NIST PMI artefact

Table B-14 PMI and features, CTC 3.

PMI Name	PMI Type	Feature	NIST PMI identifier
TOL01_PR	Surface profile	HEXAGON_FACE_01	007
TOL01_PR	Surface profile	HEXAGON_FACE_02	007
TOL01_PR	Surface profile	HEXAGON_FACE_03	007
TOL01_PR	Surface profile	HEXAGON_FACE_04	007
TOL01_PR	Surface profile	HEXAGON_FACE_05	007
TOL01_PR	Surface profile	HEXAGON_FACE_06	007
TOL03_D	Diameter	HOLE_01C	008
TOL04_PE	Perpendicularity	END_FACE	021
TOL05_D	Diameter	HOLE_01B	003
TOL06_TP	Position	SLOT_01	033
TOL07_PR	Surface profile	CORNER_FACE_PLANE	048
TOL07_PR	Surface profile	CORNER_FACE_RAD	048
TOL08_A	Angularity	V_NOTCH_FACE_LH	004
TOL09_D	Diameter	HOLE_01A	003
TOL11_FL	Flatness	DATUM_A	017
TOL12_D	Diameter	HOLE_01D	008
TOL14_TP	Position	SLOT_02	033
TOL15_1_CYL	Cylindricity	HOLE_02_1	N/A
TOL15_2_CYL	Cylindricity	HOLE_02_2	N/A
TOL15_3_CYL	Cylindricity	HOLE_02_3	N/A
TOL15_CYL	Cylindricity	HOLE_02	N/A
TOL16_1_D	Diameter	HOLE_02_1	001
TOL16_2_D	Diameter	HOLE_02_2	001
TOL16_3_D	Diameter	HOLE_02_3	001
TOL16_D	Diameter	HOLE_02	001
TOL17_CYL	Cylindricity	HOLE_01C	N/A
TOL18_CYL	Cylindricity	HOLE_01B	N/A
TOL19_CYL	Cylindricity	HOLE_01A	N/A
TOL20_CYL	Cylindricity	HOLE_01D	N/A

Notes:

1. Hole 02[_n] are the small holes in the middle
2. Hole 01[X] are the large holes on the outside, with A and B used as datum features
3. The test case identified by NIST with ‘002’ was not performed because the holes in the side of component were not manufactured (this would have required additional set-up during manufacturing)
4. The two surface profile PMI were analysed for each individual face due to current limitations within UES
5. Cylindricity PMI were not called out in the NIST test cases.

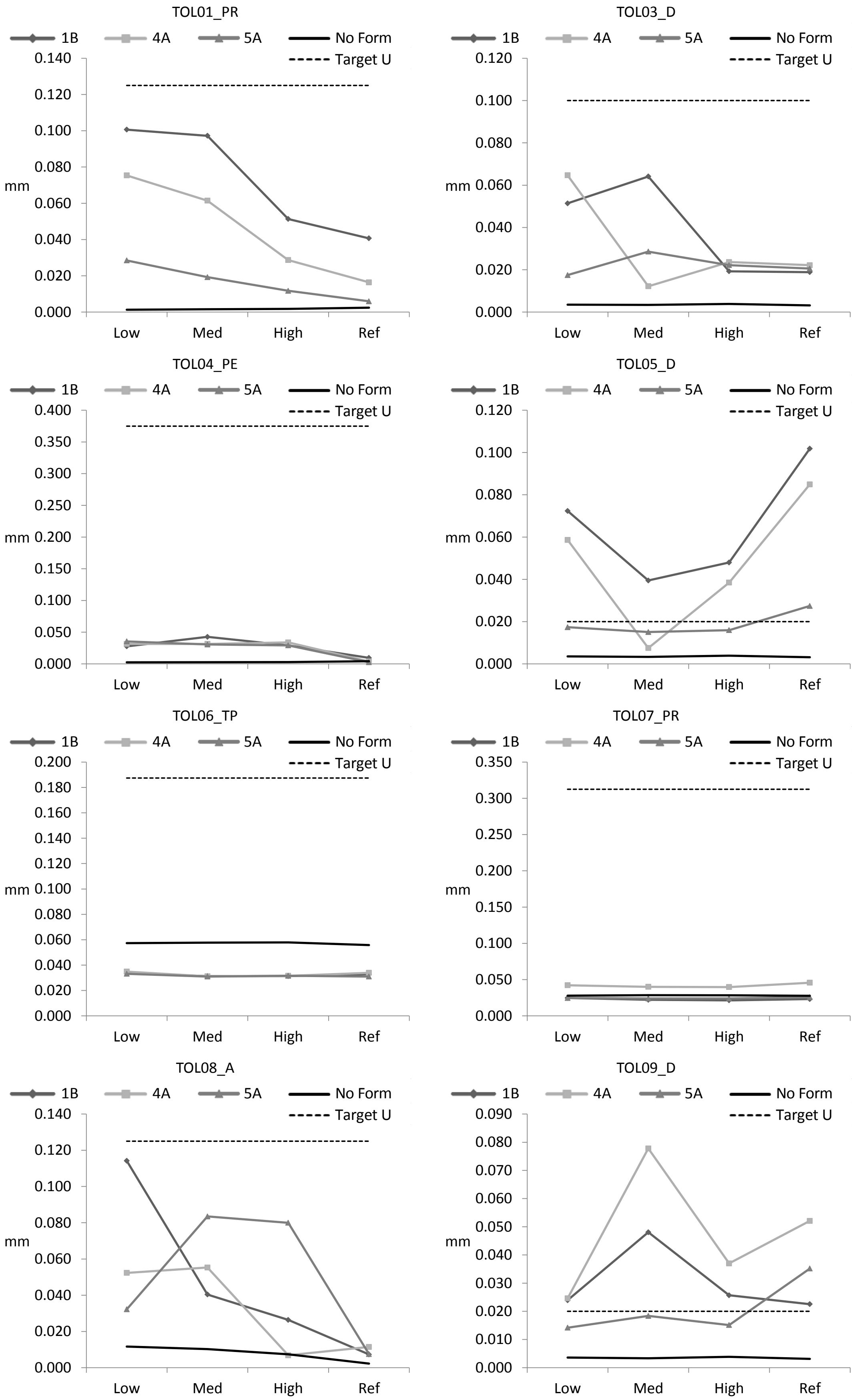

Figure B-23 U_{sim} and U_T, heartbeat artefacts, CTC 3 (fig. 1 of 3).

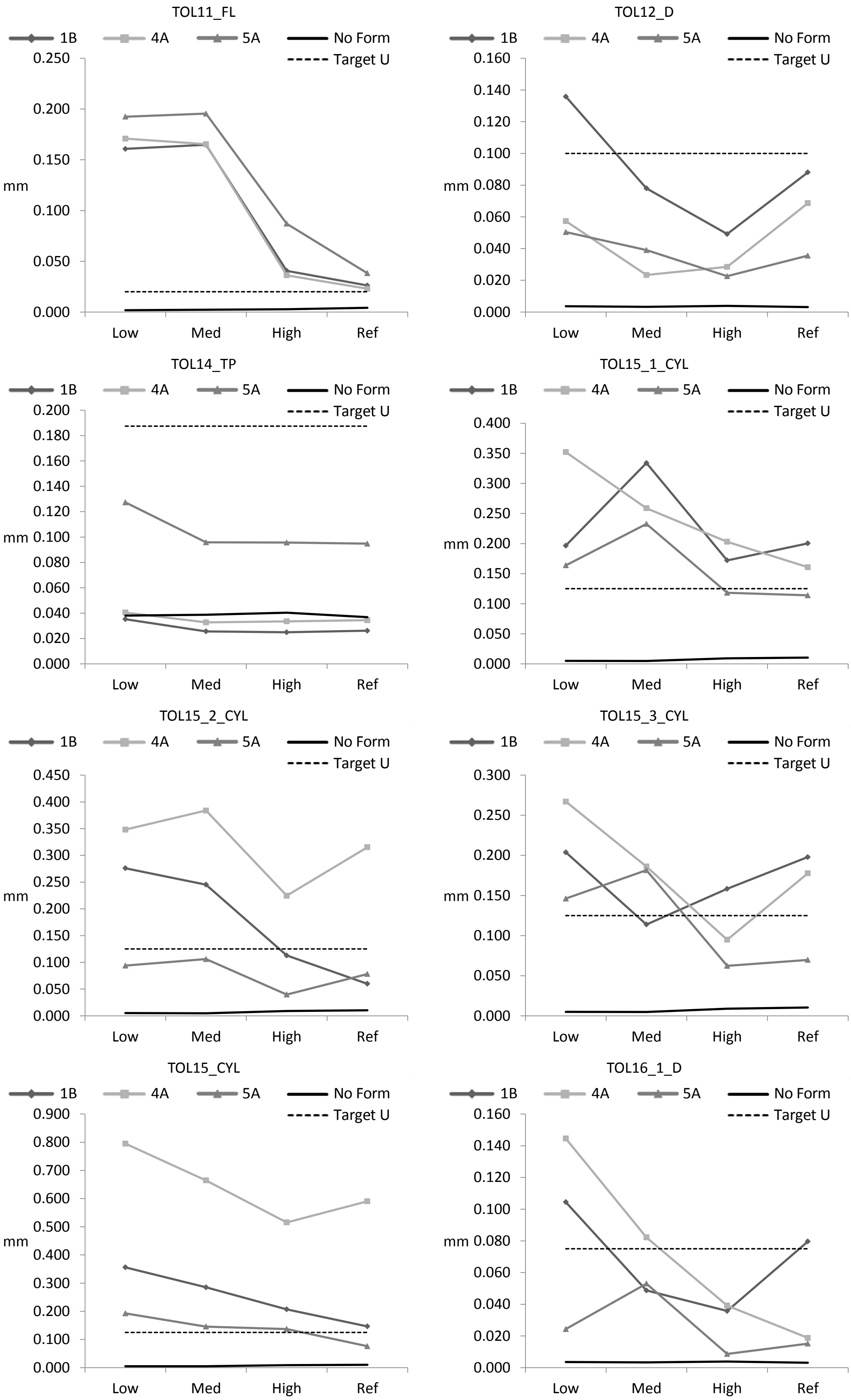

Figure B-24 U_{sim} and U_T, heartbeat artefacts, CTC 3 (fig. 2 of 3).

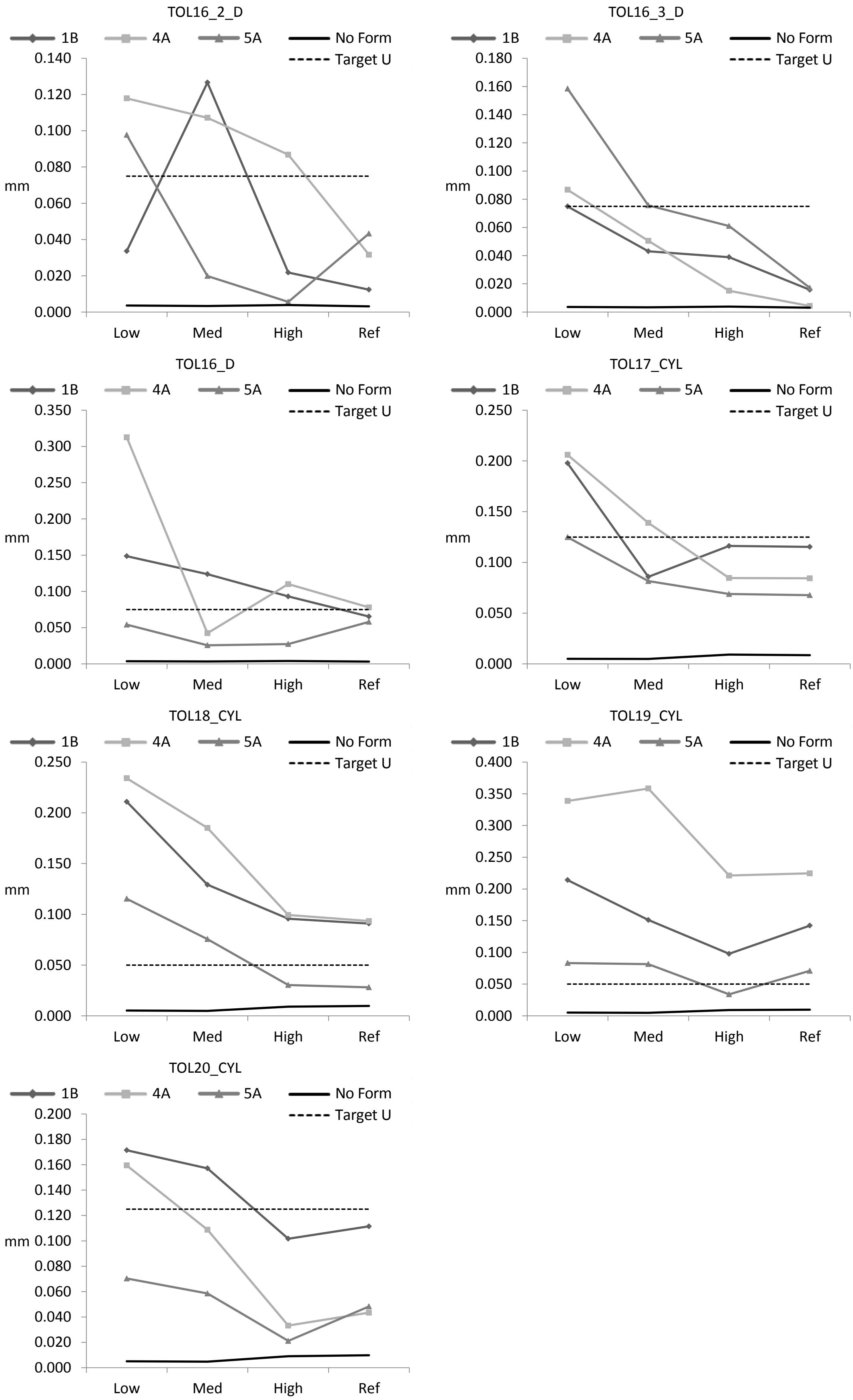

Figure B-25 U_{sim} and U_T, heartbeat artefacts, CTC 3 (fig. 3 of 3).

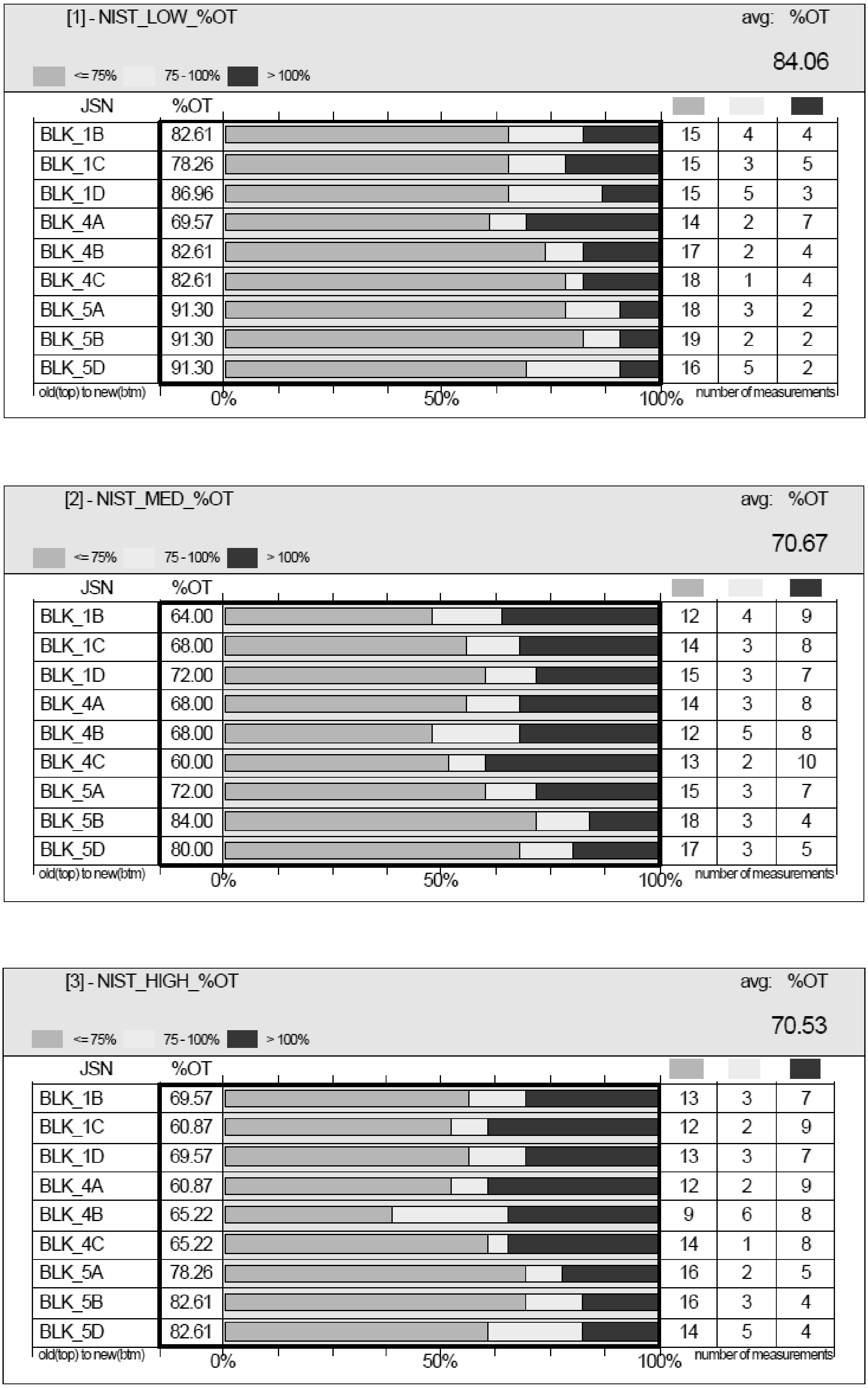

Figure B-26 Percentage on target (%OT) by method level, CTC 3.

Appendix C Supporting dataset for the industrial validation study

Rolls-Royce		Metron Pre-work Worksheet (Q1 Template - Problems)		
Question 1:		What problems could the integration of measurement processes with PLM help with?		
		Example: Version Control	Issue 1: [Insert Name]	Issue X: [Insert Name]
What?	What is the problem?	*Authoring and change management of a CMM measurement program may not be under version control*		
Where?	Which processes are affected?	*All (1,2,3,4,5,6,7,8)*		
When?	When in the product life? (NPI, CI, AfterSales etc.)	*NPI and CI*		
Extent?	How important is this issue? High=Customer Escape; Low=Internal Cost	*High - possibility of version conflict between part definition and measurement program*		
Evidence	Evidence that this is a problem - e.g. cost, lead time	*Recent history in our SCU*		

Figure C-1 PiDM scoping survey: identifying problems (before workshop).[8]

Top 8 Problems (and why)

1. **Use of different CMM programming methods (count:8)**
Inconsistent measurement results; long authoring/validation time; restricts ability to move programming between sites
2. **Changes in design need new programs (count:4)**
Increased cost and lead time from creating measurement programs due to an inefficient process - especially during NPI
3. **Long lead time for CMM program authoring (count:4)**
Program authoring takes a long time to do - both the process itself & gathering required info (e.g. PMI)
4. **Use of incorrect version of CMM program (count:4)**
Potential for lack of integrity between design and measurement programs (quality escapes); possible duplication of work
5. **Different CMMs need different programs (count:3)**
Specialist, and often scarce, programmers required; impacts cost and lead time; restricts versatility; potential business continuity issues.
6. **Poor understanding of PMI (count:2)**
Potential for incorrect measurement programs
7. **Lack of CMM programmers (count:2)**
Cost and time to create programs
8. **Metrology data is not used to improve design or manufacturing (count:2)**
Lost opportunity to improve design and manufacturing processes

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Figure C-2 Output of PiDM scoping survey: identifying problems.

[8] NPI = New product introduction; CI = Continuous improvement; SCU = Supply chain unit.

Rolls-Royce		Metron Pre-work Worksheet (Q2 Template - Opportunities)		
Question 2:		What is your vision for the full scope?		
		Example: Non-contact support	Opportunity 1: [Insert Name]	Opportunity X: [Insert Name]
What?	What is the opportunity?	*Support for non-contact technology via full 3D CAD offline programming*		
Where?	Which processes would this support or improve?	*Would widen support of measurement equipment in all processes - especially from 3 to 8*		
When?	When in the product life? (NPI, CI, AfterSales etc.)	*NPI, CI, Repair (e.g. in repair analysis)*		
Extent?	How significant is the opportunity? High = Improved product function; Low = More efficient process (hours v. [illegible]	*High - wider availablility of 3D measurement data could improve our knowledge of how geometry affects function*		
Evidence	How does this link to business strategy?	*Fewer CMMs, more non-contact being purchased. Within 5 years spend on non-contact will overtake CMMs in [illegible]*		

Figure C-3 PiDM scoping survey: identifying opportunities (before workshop).[9]

Top 7 Opportunities (and potential benefits)

1. **Standardise CMM programming strategies, incl. GD&T (count:9)**
Reduced costs and variation; simplifies measurement programming; product integrity as improvements based on existing methods
2. **Include PMI in the master model (count:3)**
Improved efficiency and increased business opportunities through becoming an industry leader in MBD
3. **Standardise measurement programming platform (count:3)**
Supports aim of global programming regardless of CMM brand (interoperability)
4. **Associate measurement data with design data (count:2)**
Improved product function and RFT
5. **Digital verification and validation of measurement process (count:2)**
Reduce iterations in method planning (reduced NPI lead time)
6. **Enable full traceability of the part (count:2)**
Mandatory for product integrity
7. **Automated CMM programming routines (count:2)**
Fewer people required, higher productivity and quality in programming. CI for existing programs easy to apply.

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Figure C-4 Output of PiDM scoping survey: identifying opportunities.[10]

[9] NPI = New product introduction; CI = Continuous improvement; SCU = Supply chain unit.

[10] MBD = Model based definition; RFT = Right first time.

Rolls-Royce	Project Metron Planning Wrap-up Questions (21st May 2013)
Name	
Business	
Are you interested in moving this forward?	
Do you want to be an active participant?	
What is your primary topic of interest / focus?	

Figure C-5 PiDM scoping survey: identifying focus (after workshop).